An investigation of the radiation damage experienced by the CCDs on the Gaia focal plane

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by

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ABSTRACT

The European Space Agency’s Gaia spacecraft was launched in December 2013 with the aim of making the largest and most precise map of the Milky Way by taking measurements of over one billion astronomical objects. It has a payload of 106 charge-coupled devices (CCDs) to help achieve its objectives. During the pre-flight testing phase of the mission, the non-ionizing energy loss (NIEL) radiation damage on the detectors was identified as a major factor that would affect the science goals of the mission. From analysis of the in-flight data, the degradation of the CCDs from radiation damage, measured as the charge-transfer inefficiency (CTI), was found to be significantly less than what was predicted from the pre-flight on-ground tests.

This thesis further investigates the radiation damage of the Gaia CCDs to more precisely understand the CTI behaviour; this helps to maintain credibility in the pre-flight tests and to better prepare for future space missions. Further in-flight data is analysed and a number of new insights are revealed about the data, related to differences in behaviour between device variants and the nature of radiation damage across Gaia’s focal plane. Different factors that have combined to result in the lower in-flight CTI measurements are also studied with analysis of on-ground data and the use of different simulation models to better understand the datasets. Finally, all these factors are combined together to make an assessment on the CTI differences between Gaia’s in-flight and on-ground CCDs and propose future testing to determine any additional sources of radiation.

Keywords: Gaia, CCD, Radiation Damage, ESA, Charge-transfer inefficiency, protons.
DECLARATION

I hereby declare that no part of this thesis has been previously submitted to this or any other university as part of any other degree or professional qualification. This thesis has been wholly written by the undersigned, except for colleagues and others acknowledged in the text.

Saad Ahmed
2022
Dedication

This thesis is dedicated to my mother and father
I would like to give a heartfelt thanks to everyone in my life who has helped me through my PhD journey. The last four years of my life has been a difficult time, not least because of the fact that I’ve had to complete half of my PhD in the midst of a global pandemic. It is absolutely true that I would not have been able to complete this without the colleagues, friends and loved ones who have supported me along the way.

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Finally a big thank you to my family, in particular my parents, siblings and aunts, for their immense love, support and enthusiasm throughout this journey.
LIST OF PUBLICATIONS

The results from the work in this thesis are partly contained within the following publications:

1. Ahmed, Saad; Hall, David; Crowley, Cian; Skottfelt, Jesper; Dryer, Ben, Seabroke, George; Hernandez, Jose; and Holland, Andrew (2020). Gaia CCDs: charge transfer inefficiency measurements between five years of flight. In: *X-Ray, Optical, and Infrared Detectors for Astronomy IX* (Vol. 11454, pp. 155-166). SPIE.

2. Ahmed, Saad; Hall, David; Crowley, Cian; Skottfelt, Jesper; Dryer, Ben; Seabroke, George; Hernandez, Jose; and Holland, Andrew (2022). Understanding the evolution of radiation damage on the Gaia CCDs after 72 months at L2. In: *Journal of Astronomical Telescopes, Instruments, and Systems*, 8(1), p.016003.

3. Ahmed, Saad; Hall, David; Skottfelt, Jesper; Dryer, Ben; Holland, Andrew; Crowley, Cian; and Hernandez, Jose (2022). Modelling the impact of radiation damage effects in in-flight and on-ground irradiated Gaia CCDs. In: *Journal of Instrumentation* 17(8) C08010.

4. Ahmed, Saad; Hall, David; Skottfelt, Jesper; Dryer, Ben; Holland, Andrew; Crowley, Cian; and Hernandez, Jose (2022). Modelling charge transfer inefficiency in Gaia CCDs with in-flight and on-ground data. In: *X-Ray, Optical, and Infrared Detectors for Astronomy IX*. (Vol. 12191, pp. 518-526). SPIE.
“You can never know everything, and part of what you know is always wrong. Perhaps even the most important part. A portion of wisdom lies in knowing that. A portion of courage lies in going on anyways.”

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CHAPTER 1

Introduction

1.1 Context

Gaia is an ambitious European Space Agency (ESA) mission that was launched on the 19th of December 2013 as part of the Horizon 2000 Plus programme. Its mission goals are to:

- measure the positions of > 1 billion stars in the Milky Way and in the Local Group to an accuracy of 20 microarcseconds.
- perform spectral and photometric measurements of most of the objects it observes.
- derive space velocities of the galaxy’s constituent stars using proper motions and stellar distances.
- create a three-dimensional map of the Milky Way.

The gathered datasets have been providing astronomers with a wealth of information that is being used to answer several questions from a wide range of research fields such as cosmology, general relativity and Solar System studies.

To help achieve its objectives, the Gaia spacecraft has a focal plane that consists of 106 charge-coupled devices (CCDs). CCDs are silicon-based digital detectors that have been used in a variety of different space missions. Gaia’s CCDs are spread across different instruments which each have different functions and collectively make measurements of stellar astrometry, photometry and spectroscopy.

The drawback of using a CCD in space is that they are highly susceptible to radiation damage. Space-bourne radiation can increase the charge transfer inefficiency
(CTI) of the CCDs which is a quantified measurement of the amount of charge loss and distortion in the signals. Radiation damage was a known factor that would influence the performance of the Gaia mission and was studied extensively in its mission development.

Measurements of charge calibration data from Gaia have revealed that the in-flight CTI has been less than what was predicted from the pre-flight tests. The difference has been such that the CTI levels have not constrained the mission timeline, helping Gaia to operate beyond its nominal mission lifetime of five years. While this result has been very beneficial for the science objectives of the mission, it becomes important to study and understand the reasons for why this has occurred.

1.2 Aims

The aim of this work is to understand and quantify, as best as possible, the reasons behind the discrepancy between the in-flight and on-ground CTI results in the context of the Gaia mission. This is important to maintain credibility of the pre-flight tests of space missions. This work is also important for understanding the performance and metrics of the Gaia mission and CCD technology. This can positively feedback into the feasibility studies of other space missions, such as ESA’s Euclid mission or the joint ESA-CSA SMILE mission, by bounding the results of radiation damage studies and providing more accurate metrics for mission lifetime, performance and longevity.

This work has been part of a studentship, co-funded by the Science and Technologies Facilities Council (STFC) and Teledyne e2v (Te2v). The work has been funded and supervised by the Open University (OU) and Te2v as part of the Centre for Electronic Imaging (CEI), a research group, specialising in the research of silicon imaging sensors for space applications. This work has also been partly funded by the European Space Agency as part of a Network Partnering Initiative (NPI) between the CEI and ESA.

1.3 Thesis organisation

The original plans for this PhD included experimental analysis as part of the NPI with ESA. This would have involved using the Gaia test bench at ESTEC as well as performing further irradiations on CCDs. These results would have been complementary
to the in-flight CTI results and would have revealed additional insights into the results of this thesis. Unfortunately, this was not possible due to the covid-19 pandemic and the subsequent international travel restrictions and global lock-downs. As a result of the pandemic, the thesis plan was modified to have more theoretical and simulation-based work whilst still maintaining the broad objectives of the thesis. While a very good set of results and procedures were devised given the circumstances, particular follow-up investigations were not possible.

This thesis is organised into ten chapters with Chapter 1 being this introductory chapter.

Chapter 2 gives an overview of CCD technology and operation. The first half of the chapter provides a description of the CCD operation details that are most relevant for this thesis. The second half of the chapter describes the interactions of radiation on CCDs, with an emphasis on CTI effects.

Chapter 3 provides a historical overview of astrometry and parallax measurements to provide context for the Gaia mission. It then describes aspects of the Gaia mission itself and links the discussion back to the CCDs of Gaia and their operation.

Chapter 4 outlines the main results of previous radiation damage studies that were performed on the CCDs of the Gaia mission. It goes through different investigations that were performed before detailing some of the in-flight CTI measurements and comparing the pre-flight and in-flight results. The chapter then goes through the potential reasons for the differences, as a precursor to the rest of the thesis.

Chapter 5 describes the analysis and results from a set of in-flight data that was obtained early in Gaia’s mission. This data was specifically for a subset of Gaia’s CCDs, forming the Radial Velocity Spectrometer (RVS). The CTI results are discussed in the context of a CCD feature called the Supplementary Buried Channel (SBC) and the CCDs’ year of manufacture.

Chapter 6 describes the analysis and results from a second set of in-flight data. Compared to chapter 5, this data is taken over a six year period across all the CCDs that are part of Gaia’s science instruments. This chapter details the CTI results in the parallel and serial directions of transfer and reports on the results with respect to the mission lifetime and the results from previous studies.

Chapter 7 quantifies the effect of straylight on CTI measurements by analysing a
set of on-ground charge calibration data. The chapter investigates the relationship between straylight and a number of different factors before providing a metric for how background straylight can affect the CTI of CCDs.

Chapter 8 quantifies and compares the radiation dose received by the in-flight and on-ground CCDs. This is done by novel investigations which model the charge data described in the previous chapters by using simulations developed to analyse CTI effects. These simulations are the Charge Distortion Model (CDM), through the use of the Pyxel pipeline, and the CCD Charge Transfer Model (C3TM). Using the simulation models, the trap defects responsible for the measured CTI effects are outlined and compared to get a metric for how the radiation dose affects the CTI.

Chapter 9 quantifies the impact of the irradiation temperature on the CTI of CCDs. This chapter provides a brief discussion of the potential temperature impacts before using C3TM simulations and results from other studies to get a metric for how the temperature of irradiation could affect the CTI of Gaia’s CCDs.

Chapter 10 finally combines all the results and quantified factors together to provide an explanation for the differences between Gaia’s in-flight and on-ground CTI results. Pertinent results of this work are presented and highlighted as avenues for further investigations.
CHAPTER 2

CCDs and the space radiation environment

2.1 The Charge Coupled Device (CCD)

The charge-coupled device (CCD) is the detector of choice for many astronomical space missions because of its excellent sensitivity, linearity and dynamic range. The focus of this thesis is on the study of radiation damage effects in the CCDs of the Gaia spacecraft with a particular emphasis on the variations between in-flight and on-ground results. A fundamental working understanding of the CCD and its operation is required to understand the impacts of radiation damage. This chapter provides a summary of CCDs and their key characteristics that are important to this thesis; a more detailed overview can be found in Janesick (2001) and Sze (1985).

CCDs were invented in 1969 in Bell labs by William Boyle and George E. Smith, initially as a memory storage device. It was discovered that they could also function as an imaging device (Boyle and Smith 1970). Throughout the years, CCDs and CCD technology have undergone many developments and advancements, making their measurements more and more precise. CCDs have a long heritage of use in many different space missions such as XMM-Newton and the Hubble Space Telescope (Strüder et al. 2001, Windhorst et al. 2011).

All CCDs have a Metal-Oxide-Semiconductor (MOS) structure. The “metal” layer, commonly polycrystalline silicon, is divided into sub-elements called electrodes which are connected to a circuit which controls the applied voltages. The semiconductor layer is typically made of silicon and is doped at different layers for device operation. The oxide-layer acts as an insulator between the metal and semiconductor layers.

The CCD is usually divided into two main sections, an image area where signal is collected, and a serial register, which transfers charge for digital conversion; both
these sections are illustrated in Figure 2.1. The image area consists of several different pixels, each of which have a number of electrodes (usually 3 to 4), which are separated with channel stops, created from implant doping in the silicon, to prevent charge from drifting.

During CCD operation, electrons are generated in the silicon substrate from the photoelectric effect when photons from a target object interact with the silicon. To retain the signal and prevent the electrons from recombining with holes, a positive voltage is applied to the metal electrodes which attracts the electrons and repels the positively charged holes. The oxide layer separates the electrons from the electrodes and prevents the two from interacting. A potential well is formed under the electrode where all the incoming electrons are stored.

As more light falls onto a CCD, the potential well under the positively charged electrode will attract more electrons until it is full. Images are usually created by “integrating” or exposing the CCD for a length of time to build sufficient charge. Initially, only some of the electrodes are positively charged and the rest of them are set to 0V. Voltage pulses or “clocks” are applied to the electrodes which changes their voltages sequentially and transfers the potential well electrode by electrode across the device to the serial register. The serial register has a similar structure to the image area but in an orthogonal direction and usually transfers charge at a faster speed. At the end of the serial register is an amplifier which measures the size of the charge packet and converts it into a digital voltage value.

2.1.1 Charge generation

As mentioned previously, charge is generated by the photoelectric effect. Incident photons that have a large enough energy can generate electrons, called photo-electrons, in the light sensitive semiconductor. The photons need to have enough energy to impart to the electrons so that they can overcome the band-gap and transition from the semiconductor’s valence band to the conduction band. In silicon, the band gap is typically 1.12 eV at 298 K (Sze 1985). If the photon energy is less than the bandgap, then no photoelectrons are generated and no photons are detected. A photon energy of <3.1 eV leads to a generation of a single electron-hole pair and a photon energy >3.1 eV produces multiple electron-hole pairs (Janesick 2001).
Fig. 2.1 Top-down view of a schematic of a three-phase CCD with a two-phase serial register towards the right. CCDs are manufactured with many hundreds or thousands of rows and columns of pixels.

2.1.2 Charge storage

Once the photoelectrons are generated, they are collected and stored within the CCD pixel through potential wells generated in the device. This is made possible due to the structure and geometry of the CCD which consists of electrodes layered on an insulator and silicon substrate.

The silicon is doped with different dopant atoms to produce an excess of either negative (electrons) or positive (holes) charge carriers; this forms n-type and p-type silicon respectively. When these two types of silicon are put together, a p-n junction is formed at the boundary. At a p-n junction, majority charge carriers from both layers diffuse across the interface until an equilibrium is reached forming a region of fixed charge space called a “depletion region”. Due to the charged ions left behind, the depletion region will have an inherent electric field directed across the junction which resists further diffusion. When a photon interacts within the depletion region and creates an electron-hole pair, the electron and the hole will be accelerated out of the depletion layer by the electric field in opposite directions (Sze 1985).

Most modern devices have an implanted layer of dopant atoms near the oxide-semiconductor interface. This causes a displacement of the potential well maximum.
away from the oxide-semiconductor interface into the substrate, forming a buried channel region and profile, detailed in Figure 2.2 where it is contrasted against a surface channel profile. Photogenerated electrons will now be held far enough away from the oxide-semiconductor interface so that they will not interact. The altered potential well acts as the primary location for charge storage within the device and improves the charge transfer efficiency (Janesick 2001).

**Fig. 2.2** Potential profiles of both a surface channel CCD (green) and a buried channel CCD (red); in the latter case, the peak of the potential well is shifted deeper into the device, moving the charge storage location away from the Si – SiO\(_2\) interface. The peak potential profile is given by the gate voltage \(V_{\text{gate}}\) in the case of surface channel CCDs, and is given by the peak potential of the gate and buried channel, \(V_{\text{gate}+\text{BC}}\) in buried channel CCDs. This figure is replicated from Figure 3.4 of Janesick (2001)

### 2.1.3 Charge transfer

After charge generation and collection, the charge must now be transferred pixel by pixel to the output node for charge conversion. This is accomplished by using potential wells created within each pixel and electrode; charge transfer is realised though the sequential applications of voltages to the electrodes. Charge is first transferred in the parallel direction across the device to the serial register where it is transferred to the readout circuits in the orthogonal direction.
Figure 2.3 details the operation of a three-phase CCD with the steps outlined as follows.

1. The phase 1 electrode voltage $\phi_1$ would be set to high and the other phases are set to zero so charge will collect under this phase.

2. Then $\phi_2$ is biased so the potential well is spread out between phases 1 and 2 and the signal distributes across the phases.

3. $\phi_1$ is then set to zero so the charge transfers completely to $\phi_2$.

4. After this, $\phi_3$ becomes biased so the charge spreads between phases 2 and 3.

5. $\phi_2$ is then biased to zero to move the charge to $\phi_3$.

6-7. Finally, $\phi_1$ is biased again and $\phi_3$ is biased to zero so the charge moves to the next pixel and the whole process repeats again.

Fig. 2.3 The charge transfer schematic for a three-phase device with the state of the potential wells at each stage. The positive voltage is in the downwards direction.

The proportion of charge that is successfully transferred is quantified as the charge transfer efficiency (CTE). The charge transfer inefficiency (CTI) is simply the CTE
subtracted from 1, as given in equation 2.1

\[ CTI = 1 - CTE \] (2.1)

A CTE of 99\% means that on average, 99\% of the charge survives a single charge transfer process. Early CCDs would exhibit 99\% efficiency per pixel transfer; while this does not seem bad, the loss compounds with each transfer. The charge read at the output node would be \(0.99^n\) (where \(n\) is the number of transfers), which means that significant quantities of signal might be lost after several transfers, making it challenging to employ large devices with a wider image area. Developments in CCD technology have managed to improve the CTE of most CCDs to about 99.999999\% where one electron per million electrons is lost from a transfer (Janesick 2001); further improvements can be made by using specialised clocking schemes (Hall et al. 2012). The operation of CCDs in space means that there will be some level of CTI increase in time, as detailed in the next section.

2.1.4 Charge measurement

After the charge has been transferred to the serial register and output, it is converted to a digital signal to be readout. This is achieved with the help of a voltage amplifier which produces a voltage that is proportional to the quantity of charge in the packet. The output circuit is customised and optimised in different ways to reduce the noise of the measurements, however this is beyond the scope of the thesis.

2.2 Space Radiation Environment

In the context of this thesis, radiation damage is the degradation of the performance of devices due to the environment in space. Interplanetary space is not a vacuum but is composed of neutral particles, plasmas, cosmic rays, micrometeoroids, and space debris, all of which can impact spacecraft and their instruments. Radiation in space predominantly consists of the electromagnetic spectrum and energetic, subatomic particles like protons, neutrons and electrons. For most spacecraft, the biggest sources of radiation are the Van Allen belts, galactic cosmic rays and solar particles from the solar wind.

The solar wind consists of a flux of charged particles from the Sun and it is largely
composed of ionized Hydrogen in the form of protons and electrons (∼90%). It also has an ∼ 8% component of alpha particles and trace amounts of heavy ions and atomic nuclei (such as Carbon and Oxygen) that have been ripped apart from the heating of the Sun’s corona (Galvin et al. 1996, Feldman et al. 1998). Occasionally, solar events such as coronal mass ejections and solar flares can cause large outbursts of particles from the Sun as well. The flux of particles from the Sun varies over time and is tied to its 11-year solar cycle (Hathaway 2015, Reames 2013).

The Gaia spacecraft is orbiting the second Earth-Sun Lagrange Point (L2), which is 1.5 million km from the Earth. Lagrange points are points of equilibrium for smaller bodies, such as spacecraft, that are under the gravitational influence of two larger bodies, such as the Earth and Sun. At Lagrange points, the gravitational pull of the two large bodies is equal to the centripetal force required by the satellite to move with them. L2 is located on the “night” side of the Earth and spacecraft docked here can observe the larger universe without the Earth distorting its view (Cornish 2018).

As L2 is well outside the influence of the Earth’s magnetosphere, this means the radiation of the Van Allen belts can be ignored. The largest sources of radiation present at L2 are the galactic cosmic rays and the solar wind (Kohley et al. 2014). A number of different radiation models exist to simulate the radiation environment and get a prediction for the expected dose of spacecraft. The radiation environment at L2 was expected to be dominated by solar wind protons and as such, galactic cosmic rays were neglected in the pre-flight analysis. The flux of particles from GCRs has an inverse relationship with the flux of particles from the Sun, which was expected to be very active (Hathaway 2015). Regardless of the radiation source, high-energy particles can cause different effects in CCDs, the primary ones being ionizing damage and non-ionizing damage (Janesick 2001).

2.3 Ionizing Damage

When energetic particles collide with a material, they can transfer either part or all of their energy to the target material, causing either ionizing or non-ionizing damage. The energy lost by the incident particles through ionization is quantified as the Total Ionizing Dose (TID) and can lead to the generation of electron-hole pairs. Ionizing radiation can cause temporary effects where the state of an electronic device is altered by the incident
particles; these are called Single Event Upsets (SEUs). The TID can also cause more long-term effects such as voltage shifts and increasing dark current (Hopkinson et al. 1996); these effects are routinely monitored in the Gaia devices. Figure 2.4 details the ionizing and non-ionizing damage mechanisms.

### 2.4 Non-ionizing damage

#### 2.4.1 Damage mechanisms

The energy lost from incident particles through non-ionizing damage is quantified as the Non-Ionizing Energy Loss (NIEL). NIEL causes long-term damage to CCDs through displacement damage in the silicon lattice of the CCD. Non-ionizing damage takes place with the displacement of atoms from their positions in the silicon. This displacement is caused by elastic scattering from the incoming particles. The scattering is caused by either electrostatic or nuclear interactions, depending on the energy of the incoming particle.

The recoiling target atom is usually referred to as the primary knock-on atom (PKA). PKAs can additionally cause a series of atomic displacements in the silicon that can leave clusters of defects through the material. In silicon, if the energy transferred to the displaced material exceeds a threshold (2.3 eV in Si), then the displacement leads to the formation of atom-vacancy interstitial pairs. These are known as Frenkel pairs, consisting of an interstitial silicon atom and a vacancy. These are unstable and generally recombine back together. Sometimes, however, they may form stable configurations with other vacancies or impurities such as doping atoms (like phosphorus or boron), or impurity atoms from the CCD manufacturing process (like carbon or oxygen). These vacancy and impurity complexes are referred to as bulk traps and complexes of specific natures are called trap defects. These trap defect species can increase the CTI of CCDs (Srour et al. 2003). The process of trap-defect creation is illustrated in Figure 2.4.

#### 2.4.2 CTI effects

Trap defects increase the CTI of CCDs by introducing energy levels between the conduction and valence energy bands of silicon. These energy levels can capture and release electrons from signals on characteristic timescales. The capture and release from
A summary of the ionizing and non-ionizing effects of radiation damage, adapted from Srour et al. (2003) (image is not to scale).

trap defects is governed by the Shockley-Read-Hall equations and is modelled as a decay process. The time constants for capture and emission ($\tau_c$ and $\tau_e$ respectively) depend on the type of trap defect and corresponding energy level, as well as the operating temperature and the capture cross-section of the traps (Shockley and Read Jr 1952).

Different trap defect species have different energy levels and capture cross-sections which results in the defects causing different effects when transferring signals in CCDs at specific transfer speeds. These effects can be controlled and altered by the operating temperature of the device and the transfer speed, $t$. Once the charge is captured by a trap defect, then there are three possible outcomes.

If $\tau_e << t$, then the captured charge is almost immediately emitted back into the charge packet before it is transferred and there is no distortion or loss of signal. If $\tau_e >> t$, then charge is released long after the signal has been transferred resulting in an overall charge loss from the signal. Finally, if $\tau_e$ is on a comparable timescale with $t$, then the signal becomes distorted as charge is lost from the signal and emitted into the pixels following the signal, causing charge tails to form, trailing after the signal. Figure 2.5 details the distortion of data from charge tails.

The CCD transfer speed for the Gaia CCDs, as well as for most devices, is different between the parallel and serial directions. As the transfer speed partially defines the behaviour of a trap defect, this means that alternate CTI effects will be observed in both
2.4.3 Trap defects

Many different radiation-induced trap defects have been identified and studied extensively using Deep Level Transient Spectroscopy (DLTS) in older studies (Srour et al. 2003) and by using newer techniques such as “trap pumping” in more recent studies (Hall et al. 2014). Much of these defects arise due to impurities found in silicon from the CCD manufacturing process. In the context of the CTI results of this thesis, as well as considering Gaia’s operating temperature and clocking speeds, three particular defects are of interest to study. Namely, they are the divacancy, a defect referred to as the “unknown”, and a species referred to as a continuum of defects (Bush et al. 2021, Parsons et al. 2021); further details are described in Chapter 8.

2.5 Radiation-induced damage in the context of Gaia

Radiation damage, and the subsequent CTI, was a known factor that would affect the performance of Gaia’s devices and in turn, the science objectives of the mission. To combat CTI and study the effects of trap defects in more detail, a number of different
strategies and mitigation techniques were devised. Radiation Campaigns unique to Gaia were also conducted, as detailed in Chapter 4, to explore these effects. Before the specifics of these techniques and results are discussed, Chapter 3 gives an overview of the Gaia mission itself, as well as the specific CCDs that were designed for the mission.
CHAPTER 3

The Gaia Mission

3.1 Introduction

The Gaia mission was launched to create the largest and most precise three-dimensional map of the Milky Way by cataloguing and making measurements of over one billion stars. The data is helping researchers discover new astronomical objects and answer many questions about the origin, structure and evolutionary history of our galaxy. To accomplish its goals and fulfil its science objectives, Gaia was uniquely designed to carry out high-precision astrometry measurements.

3.2 Astrometry

Astrometry is a particular branch of science concerned with the precise and accurate measurements of the locations and movements of celestial bodies. It has a long history that dates back to the time of the Ancient Greeks, and over the years, it has seen numerous innovations and developments as well as catalogue expansions and measurement refinements, detailed in Figure 3.1. Further insights to the detailed history of Astrometry can be found in Høg (2009).

Combining precise and accurate astrometric measurements of stars with information on their intrinsic properties is useful for interpreting and understanding stellar evolution theories. Venturing a step further and conducting a census on a galactic scale, such as with the Milky Way, allows for the study of even more topics of interest such as galactic evolution, the history of star formation and fundamental physics.

Six different parameters define the geometric and kinematic properties of celestial objects, five of which can be found using astrometric measurements. These parameters are,
Fig. 3.1  The astrometric accuracy over the past 2,000 years; it can be seen that the past 400 years brought larger but much more gradual improvements in time. The Hipparcos satellite started a new era of astrometry with measurements from space; replication of Figure 1.3 from Brown (2010). Original credit to Høg (2009)

- $\alpha$: the right ascension or longitude in the chosen coordinate system.

- $\delta$: the declination or latitude in the chosen coordinate system.

- $\mu_{\alpha}$: the proper motion, or angular change in the object’s position in the direction of $\alpha$. Units are usually milliarcseconds per year ($\text{mas yr}^{-1}$)

- $\mu_{\delta}$: the proper motion or angular change in the object’s position in the direction of $\delta$. Units are $\text{mas yr}^{-1}$

- $\pi$: the parallax or apparent displacement of a body’s position on the sky due to the Earth’s orbit around the Sun.

- $v_r$: the radial velocity or velocity along the line-of-sight, usually measured in $\text{km s}^{-1}$. While radial velocities can be inferred from astrometric measurements, they are usually found from wavelength shifts in the spectra of bodies.
3.3 Parallax

By measuring the parallax or apparent change of the motion of a star across the sky, it is possible to measure the distance of the star from the Sun. Figure 3.2 details the parallax phenomenon where stars that are located relatively closer to the Earth appear to change their position in the sky with respect to background reference stars as the Earth orbits the Sun. A star’s parallax is defined as one-half of the maximum change in angular position observed from opposite ends of the Earth’s orbit. As the stars are so far away, the small angle approximation \( \tan \theta \approx \theta \) may be used, as given in equation 3.1,

\[
\pi \equiv \frac{r}{d}
\]  

(3.1)

In equation 3.1, \( r \) is the radius of the Earth’s orbit (1 Astronomical Unit (AU) \( \simeq 1.5 \times 10^8 \) km) and \( d \) is the distance between the star and the Sun, usually measured in parsecs (1 parsec \( = 3.26 \) light-years).

**Fig. 3.2** When observing a patch of the sky from the Earth at different times of the year, some stars appear to move across a path, relative to more distant "background" stars; this motion is called stellar parallax. In (1), the star of interest is situated towards the pole of the ecliptic and appears to trace out a circle as the Earth orbits the Sun whereas in (2), the star of interest lies at an angle from the ecliptic and traces out an ellipse. If a star lied on the plane of the ecliptic, then it would trace out a line. The parameters \( r \) (1 Astronomical Unit \( \simeq 1.5 \times 10^8 \) km), \( \pi \) (the parallax), and \( d \) (the distance between the star of interest and the Sun) are related by equation 3.1.
In reality, parallax measurements are not so straight-forward. The star being observed will have its own proper and orbital motion. If it is part of a binary or multiple system, it will exhibit further orbital motion. Equation 3.1 and Figure 3.2 also assume that the background stars are located at infinity and are stationary. These background stars would have their own parallax that needs to be accounted for in the measurements. The parallax of the star of interest can be calculated by measuring the angular difference between the star of interest and the background star in the same field of view at two different epochs, as given in equation 3.2 and illustrated in the left-hand figure of Figure 3.3.

\[ \pi = \pi_0 + (\phi_2 - \phi_1)/2 \] (3.2)

In equation 3.2, if the parallax of the background star \( \pi_0 \) is ignored or unknown, a systematic error is introduced in the parallax measurement. If, however, measurements can be made of the star of interest and a reference star in two very different parts of the sky, then the parallax of the reference star could be decoupled from the parallax of the star of interest (Lindegren 2005). This wide-angle astrometry approach removes the need for \( \pi_0 \) from equation 3.2 and is illustrated in the right-hand figure of Figure 3.3.

It is difficult to perform this wide-field astrometry from the ground due to the effects of refraction from turbulence within the Earth’s atmosphere; this can dominate the error budget in ground-based observations and lead to blurred images. Observing from space, on the other hand, means that, in addition to the lack of atmospheric effects, the entire sky is visible, the thermal and gravitational stability is higher, and the level of background light is lower. The wide-angle technique requires two fields of view separated by a large enough angle for practical implementation, both of which can be accommodated on a single satellite, scanning the sky to mimic the Earth’s rotation. Space-based observatories, in other words, are ideal for performing global, absolute astrometry; the Gaia spacecraft is one such spacecraft designed to catalogue the stars. It should be noted that this discussion does not discredit ground-based observations as they still provide the initial input catalogues for researchers and space programmes.
Fig. 3.3 The parallax measurement principle. **Left:** Differential small-field measurement where the "background" star is in the same field of view as the star of interest. **Right:** Wide-angle or absolute measurement where the reference star is separated by a large angle from the star of interest; this measurement can only be feasibly performed from space. Figure is adapted from Lindegren (2005).

### 3.4 Hipparcos

Before going into detail about the specifics of Gaia, a brief commentary is worthwhile on the Hipparcos spacecraft which was the primary astrometry mission launched before Gaia. It was an ESA mission that flew between 1989 and 1993 and produced a catalogue containing $\sim 118,000$ entries. Hipparcos can be considered the predecessor to Gaia in multiple ways. It was able to combine the light from two fields-of-view, separated by a basic angle of $58^\circ$, to make large-angle measurements at high precision. It combined the light from these two views using a beam combiner and a succession of reflections which directed the light onto a focal plane. It also adopted a scanning law, scanning the sky in great circles whilst in a highly eccentric orbit around the Earth. All of the concepts were reproduced and expanded upon with Gaia.

### 3.5 The Gaia Mission

Given the success of Hipparcos, the Gaia mission was selected by the the European Space Agency in 2001 as part of the Horizon 2000 Plus programme to perform astrom-
etry measurements with more scope and accuracy. Compared to Hipparcos, Gaia was designed to be 100 times more accurate and measure even fainter objects, all the way down to magnitude $V \simeq 20.5$. After a long development and testing period, it was successfully launched on 19th December 2013 and has been orbiting and operating at L2 ever since; a location much further out than Hipparcos. The science objectives of Gaia are detailed extensively in Perryman et al. (2001). To summarise, the mission’s aims are to build a greater understanding of the Milky Way galaxy with respect to its structure, formation and evolution. The Gaia spacecraft was designed to measure the positions, fluxes and motions of approximately 1 billion stars (mapping out one percent of the Milky Way) as well as other astronomical objects that come into its field of view.

Gaia is a scanning telescope which takes repeated measurements of all the objects it observes over its mission timeline. This allows researchers to track and study the variation of the properties of astronomical objects in time. In its nominal mission duration of 5 years, it was expected to observe every object in its field of view approximately 70 times. Gaia’s accurate astrometry measurements are made possible thanks to its excellent photometry and spectroscopy capabilities. Each and every measurement made in relation to an object’s characteristics, such as position, motion, spectra, and radial velocities, make up the mission’s Data Releases (DRs) (for the latest updates on the DRs and the mission in general, see https://www.cosmos.esa.int/web/gaia/data ESA/Gaia/DPAC (2022)). All this data gives researchers a wealth of information to study and understand the fundamental properties of stars, the Milky Way and physics as a whole. Gaia’s design and instruments play a significant role in the mission’s capabilities and scientific output (Pancino 2020).

3.5.1 Payload

To perform the wide-field astrometry described previously, the Gaia spacecraft uses two optical telescopes, separated by a basic angle of $106.5^\circ$. Incoming light from both these telescopes is directed with a set of mirrors to a single focal plane, measuring $0.42 \times 0.93$ m. Figure 3.4 details schematics of the layout of the on-board optical elements and the focal plane. The entire structure is held on a silicon-carbide structure to keep it in place. There are also prisms and diffraction gratings to disperse the light for particular measurements by specialised instruments on the focal plane. A service
module supports the payload, while a thermal tent shields the entire structure. The spacecraft contains a sunshield with a 10m diameter, as illustrated in Figure 3.5, to aid in maintaining the thermal stability of the payload and service module. The sunshield was deployed once the ~2000kg spacecraft arrived in space and entered orbit (Kohley et al. 2012, Prusti et al. 2016).

**Fig. 3.4** (a) A schematic of the Gaia payload which illustrates the two primary mirrors of the two telescopes, the torus that supports the optical elements, the focal plane as well as the rotation axis. (b) A schematic illustrating how light from the two lines of sight travel through the mirror segments (M1-M6 and M’1-M’6) and arrive at the focal plane. Both illustrations are courtesy of EADS Astrium.
3.5.2 Focal Plane

Figure 3.6 highlights the focal plane with its 106 CCDs, colour coded by its different instruments. When light from astronomical objects enters the field of view, they are first encountered by the Sky Mappers (SMs). The Sky Mappers are two columns of seven CCDs, one column for each telescope, where the devices operate in full-frame mode for object detection. After getting detected by the SM CCDs, the light passes to the other instruments (De Bruijne et al. 2015). The primary instrument is the Astrometric Field (AF) which contains 8 columns of 7 CCDs, and one column with 6 CCDs; the column with 6 CCDs has a CCD referred to as Wave-Front Sensor 1 (WFS1) in the middle. The first column of the AF field also takes part in object detection and after confirming the object, assigns it a window of pixels (De Bruijne et al. 2015). This is to reduce the volume of data that returned by the spacecraft as well as the readout noise. The rest of the AF field measures and collects non-dispersed light over the wavelength range, 330-1050 nm for high-precision astrometric measurements (Prusti et al. 2016).
Fig. 3.6 The Gaia focal plane with 106 large-format CCDs. The CCDs are split into seven rows and 17 columns, each with a set of readout electronics known as proximity electronic modules (PEMs). The devices all run in synchronisation with the aid of an on-board computer. The CCDs in this figure are color-coded according to the functional group they belong to. Figure adapted from Laborie et al. (2007).

After moving along the AF field, the light is then dispersed through two different prisms for measurement of the spectra by the Photometer instruments. The Blue Photometer (BP) and the Red Photometer (RP) are both columns of 7 CCDs which are able to measure spectra in the 330-680 nm and 650-1050 nm wavelength regimes respectively. After this, if the object is brighter than $17^{th}$ magnitude and located between rows 4 and 7, its light reaches the Radial Velocity Spectrometer (RVS). The light enters a diffraction grating allowing the RVS instrument to measure high-resolution spectra in the 846-874 nm wavelength regime. This is around the Calcium IR triplet and allows for accurate radial velocity measurements for late-type stars (Kohley et al. 2009, 2012).

In addition to WFS1, there is also a Wave-front Sensor 2 (WFS2) preceding the SM instruments; both the WFSs are responsible for monitoring the optical quality of the telescopes and to support re-focusing. There are also two CCDs that make up the Basic Angle Monitors (BAM); these CCDs measure and monitor variations in the basic angle between the two telescopes.
3.6 Gaia CCDs

The CCDs used on the Gaia focal plane were specially designed and customised for the mission by Teledyne e2v. They are of the CCD91-72 variant and each have a size of $4500 \times 1966$ pixels; each pixel measures $10 \times 30 \, \mu m$ which translates to $\sim 59 \times 177$ milliarcseconds on the sky. The pixel size was chosen as a compromise between the required resolution in the along-scan (AL) direction and the full well capacity. The CCDs are back-illuminated, full-frame, four-phase devices with a two-phase serial register. Given the continuously scanning nature of the Gaia spacecraft, the CCDs operate in Time-Delayed Integration (TDI) mode which means they transfer charge synchronously with the satellite’s rotation. The TDI clock rate is 0.9828 ms which results in an effective exposure of $\sim 4.42 \, s$ for a CCD transit (Seabroke et al. 2008, Crowley et al. 2016a).

The CCDs were manufactured in three different device variants, each with the same pixel architecture but optimised for different wavelength ranges. Most of the CCDs are used for astrometric measurements and are of the AF variant device which was built on standard silicon with a resistivity of $100 \, \Omega \cdot cm$, thinned to $16 \, \mu m$, with an Anti-Reflection (AR) coating centred at 650 nm. The AF variant devices are used on the AF instrument as well as the SM and WFS instruments. Another device variant was the BP variant which was integrated on the instrument of the same name. They are similar to AF variant CCDs but were made to be more sensitive to bluer wavelengths thanks to an enhanced surface activation process and an AR coating centred at 360 nm (Seabroke et al. 2009).

The third device variant was the RP variant device that is used on the Red Photometer, the Radial Velocity Spectrometer and the Basic Angle Monitors. These CCDs required a greater sensitivity towards redder wavelengths so were fabricated on high-resistivity ($1500 \, \Omega \cdot cm$), deep-depleted silicon with a thickness of $40 \, \mu m$ and with an AR-coating centred at 750 nm (Seabroke et al. 2009). This difference in thickness and resistivity leads to some CTI differences which are discussed later in the thesis.

The Gaia CCDs were also manufactured with a number of unique features and peculiarities to aid in their routine operation. All the CCDs contain a charge-injection (CI) structure which artificially injects charge into the CCDs. The CI structure consists of an injection gate and drain located at the edge of the device. CIs help to mitigate CTI from
radiation-induced trap defects as the artificial charge occupies slow-release traps so that signals can be transferred through the CCD unperturbed. The CIs can also be used to monitor the in-flight CTI and track its evolution in time. It should be noted that while a CI structure was implemented on all the CCDs, CIs were not chosen to be used on the RVS CCDs as a CTI mitigation option as the extra photon Poisson noise was noted to be too high given the already low signal-to-noise ratio of the RVS spectra (Seabroke et al. 2013a). Another feature implemented on the devices to reduce the impact of radiation damage is the Supplementary Buried Channel (SBC). This is a notch in the buried channel region, which is created by additional doping that creates a deeper potential well. This can confine smaller signals to a smaller volume with a higher density so that they encounter fewer traps (Kohley et al. 2009, Seabroke et al. 2010).

Due to the TDI operation, there is a chance for particularly bright objects to saturate the pixel and cause charge spilling or vertical blooming into other pixels. To account for this, the CCDs were manufactured with an Anti-Blooming Drain (ABD), where excess charge drains into if the buried channel becomes saturated. There are also 12 independently controlled polysilicon TDI gates built into each CCD to account for the issue of charge saturation. These gates can be held at a barrier potential which blocks the transport of charge within that column, causing it to drain into the ABD until the gate is released. The charge from above that gate does not contribute to the signal packet, so the effective integration time is reduced (Kohley et al. 2009, Seabroke et al. 2010). The illustrations in Figure 3.7 detail schematics of the Gaia pixel with the structures and features as described with the bottom figure detailing the potential profiles from different applied voltages.

While the architecture of all the CCDs is identical, the operating mode of each instrument is very different. For example, the BAM CCDs integrate a static interference pattern and need to operate in stare mode in addition to CCD readout. A single common set of readout electronics was built by Crisa, under contract by EADS Astrium (now Airbus Defence and Space), known as the Proximity Electronics Modules (PEM) and the different operating modes are all programmable via software. More details of the PEM as well as the different operation modes and characteristics are detailed in Crowley et al. (2016a); for now, Table 3.1 details the some of the differences between the operation of the instruments that are relevant for this thesis.
3.7 Orbit and operations

Gaia was launched into orbit on 19\textsuperscript{th} December 2013 on a Soyuz-ST rocket from the European spaceport in French Guiana. It soon entered a four day Launch and Early Orbit Phase where the first activations took place followed by the deployment of the sun shield. This was then followed by a 30 day transfer cruise followed by an L2 orbit injection manoeuvre on 8\textsuperscript{th} January 2014. Once at L2, the in-flight commissioning phase
Table 3.1 Selected operating mode characteristics for the science instruments’ nominal CCD modes.

<table>
<thead>
<tr>
<th>CCD mode</th>
<th>Readout frequency (kHz)</th>
<th>Charge Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>833</td>
<td>no</td>
</tr>
<tr>
<td>AF1</td>
<td>400</td>
<td>yes</td>
</tr>
<tr>
<td>AF</td>
<td>103</td>
<td>yes</td>
</tr>
<tr>
<td>BP</td>
<td>164</td>
<td>yes</td>
</tr>
<tr>
<td>RP</td>
<td>164</td>
<td>yes</td>
</tr>
<tr>
<td>RVS-HR</td>
<td>172</td>
<td>no</td>
</tr>
</tbody>
</table>

...took place to check the operations of all the devices and instruments and to prepare the spacecraft for routine operations (Prusti et al. 2016).

Gaia operates in a Lissajous-type orbit around the second Sun-Earth Lagrange Point, 1.5 million km away from the Earth. This location offers a stable thermal environment, high observing efficiency and a relatively low radiation environment. Orbits about L2 are dynamically unstable and to maintain its orbit and position at L2, Gaia requires regular orbit maintenance manoeuvres with a chemical propulsion system. The cold-gas consumption of the micro-propulsion subsystem will limit the lifetime of Gaia to about 10 years, assuming no hardware failures. In general, Gaia’s orbit is not affected by eclipses of the Sun by the Earth although it undergoes occasional manoeuvres to maintain eclipse-free operations. The spacecraft has a revolution period of about 180 days with an orbit size of around $340,000 \times 90,000$ km (Prusti et al. 2016).

ESA’s ground stations are used to send commands to the spacecraft and receive the large volume of data transmitted. Mission operations are conducted by the Mission Operations Centre (MOC) at the European Space Operations Centre (ESOC) in Darmstadt, Germany. The science data is distributed to the European Space Astronomy Centre (ESAC) in Villafranca del Castillo, Spain, where the science operations are conducted. Further data processing is the responsibility of the Gaia Data Processing and Analysis Consortium (DPAC). The DPAC is a large group in charge of the complex and interdependent data processing tasks. It is internationally organised and split into independent coordination units (CUs) with different units responsible for cyclic data processing tasks and daily data processing. The processing takes place on hardware spread across six data processing centres across Europe which communicate with the main database located at ESAC (Prusti et al. 2016).
3.8 Overview

This chapter has outlined and provided context for the Gaia mission and has presented an overview of the spacecraft and some of the features that are relevant to the work of this thesis. Before launch, a number of different tests were conducted to verify and test the performance of the spacecraft’s various components. Having understood the Gaia CCDs as well as the impact of radiation damage on their performance, the next chapter details the pre-flight tests that were conducted before launch as well as the in-flight measurements that were performed after launch to characterise the impact of radiation-induced CTI.
CHAPTER 4

Previous studies of radiation damage on the Gaia CCDs

4.1 Introduction

During Gaia’s pre-launch development, the impact of radiation damage on the CCDs was recognised as a significant concern that would influence the performance of the mission. A number of different studies were conducted and methodologies were investigated to understand and quantify the radiation impact. A radiation calibration strategy (Seabroke et al. 2008) was devised which followed five lines of attack:

1. Minimising the radiation damage by CCD hardware optimisation methods (e.g. using charge injections or diffuse optical background strategies to keep the slower traps filled),

2. Astrium CCD hardware testing,

3. Analysis of Astrium’s CCD hardware tests by Astrium and members of Gaia Data Processing and Analysis Consortium (DPAC),

4. Implementation of radiation damage effects in simulation software to produce simulated damaged data to compare with hardware results,

5. Software calibration in the astrometric, photometric and RVS data reduction pipelines.

These lines of attack were all mutually dependent, with the results and conclusions from one study feeding back into others. A number of the CCD hardware optimisation routines have already been discussed in Chapter 3. Most of this chapter details the main results of the other pre-flight radiation damage investigations conducted with the Gaia CCDs. The rest of the chapter outlines the results from in-flight data, taken after
Gaia was launched, and compares them with the results from the pre-flight studies, bringing everything back to the focus of the thesis.

4.2 Pre-launch results

4.2.1 NIEL dose prediction

As a precursor to Gaia’s radiation damage studies, a prediction was made for the expected radiation dose on the Gaia focal plane. The result of this prediction was then used to form the basis of the subsequent experimental and simulation work. The radiation dose prediction was made in 2006 using a 3-D model of the Gaia spacecraft in a software called Systema Dosrad. This software replicated the individual components of the spacecraft as accurately as possible, down to their materials and thicknesses.

In this radiation dose analysis, the effects of Earth’s radiation belts were ignored as Gaia would only be in their vicinity for a few days. Given the orbit of the spacecraft and the predicted level of solar activity at the time, galactic cosmic rays were also neglected in the radiation dose analysis. This means that solar protons were the primary focus of the radiation dose modelling. The reference model used for this modelling was the JPL-1991 model (Feynman et al. 1993) which requires an input of a confidence level and a mission duration. The confidence level is a probability measurement; a confidence level of 90% for example would mean that 90% of the time, the radiation flux would be less than the model’s predicted values. Given the 5-year nominal mission lifetime and the initial planned launch date of December 2011, a prediction was made assuming 4 years of solar maximum activity at the 90% confidence level; this confidence level was the ESA recommendation at the time.

Figure 4.1 reproduces the predicted NIEL dose of 10 MeV equivalent protons. In Figure 4.1 it is noted that devices receive a greater dose of 10 MeV equivalence towards the centre of the focal plane, as illustrated by the pattern of NIEL values across the AF devices. The BP, RP and RVS instruments have prisms, optics and photometers mounted in front of the devices which causes a reduced impact from the 10 MeV equivalent dose, as noted in Figure 4.1. This predicted dose is what formed the basis for the irradiations in the pre-flight experimental tests. The AF CCDs were predicted to receive a dose of $3.11 \times 10^9 \text{ p}^+ \text{ cm}^{-2}$ 10 MeV equivalent protons; due to this, on-ground irradi-
ations were performed at a slightly higher level of $4 \times 10^9$ p$^+$ cm$^{-2}$ 10 MeV equivalence to overestimate the damage with a 20% safety margin (Kohley et al. 2014). The thicker RP devices, meanwhile, were irradiated to $2 \times 10^9$ p$^+$ cm$^{-2}$ at the 10 MeV equivalence (Seabroke et al. 2013a).

Fig. 4.1 A representation of the 10 MeV equivalent proton NIEL dose, measured in p$^+$ cm$^{-2}$, predicted by Airbus Defence and Space a number of years before launch in 2006. The irradiation levels for the on-ground tests were based on this set of predictions. The End-of-Mission (EoM) NIEL prediction for the CCDs ended up being lower than this at the time of launch. Figure adapted from Kohley et al. (2014).

4.2.2 Experimental studies

Astrium conducted a set of five Radiation Campaigns (RCs) to study the effects of radiation damage on the Gaia CCDs. The RCs form the bulk of the on-ground radiation damage studies that were performed for the Gaia mission. The RCs were planned by DPAC, and the objectives were to understand the effects of the radiation environment at L2 on Gaia’s instruments as well as to characterise the damage and to assess how the image distortion could best be modelled and calibrated during data processing.

The RCs studied the effects of trap defects at different signal levels and temperature. The hardware features of the CCDs were also investigated such as the Full Well Capacities (FWCs) of the Supplementary Buried Channel (SBC) and the TDI gates, the
use of which was found to reduce any systematic biases in the data. The results of the
RCs were also used to set the charge injection level and duration (Brown 2010). CTI
effects were investigated on the different device variants; interestingly, the thicker red
devices were found to be more sensitive to radiation damage (Prod’homme 2011).

A number of interesting peculiarities were revealed about the operation of the CCDs
from the RCs. Amongst them were the Proximity Electronics Module (PEM) causing
anomalies which led to background variations and the stitching of the CCDs affecting
the measurements. Insights were also revealed about the mitigating effect of diffuse
optical background on the CTI measurements. This mitigating effect was found to be
more pronounced at fainter signals and produced diminishing returns with increased
background.

The experimental results from the RCs were also compared against microscopic
and macroscopic computational models and simulations (detailed in the next section).
These comparisons were performed to better understand the CCD properties as well as
to validate the models for use in the data processing. Most of the results and conclusions
of the first three RCs can be found in Brown (2010); the rest are in internal documents
and technical reports belonging to DPAC.

Gordon Hopkinson, a researcher at Surrey Satellite Technology, performed a num-
ber of experimental tests and analyses alongside the RCs. Hopkinson studied the charge
loss and quantified the trap defects by examining the deferred charge tails from CIs and
trying to fit them with a sum of exponentials. In this analysis, it was noted that recapture
effects extended the charge trails and made it difficult to reliably model the charge tails.
For future studies, Hopkinson noted it would be useful to extend the work further with
studies that employed the use of Monte-Carlo simulations to model the charge recapture
effects (Hopkinson and Mohammadzadeh 2003, Hopkinson et al. 2005).

Hopkinson also compared the CTI effects between cryogenic and room-temperature
irradiated CCDs. Up until the time of Gaia’s launch, room-temperature irradiations
were the standard for investigating the effects of radiation damage in CCDs for space
missions. Hopkinson found that cryogenic irradiations would produce a higher con-
centration of trap defects by a factor of $\sim 2 - 3.5$ compared to room-temperature ir-
radiations. A subsequent room-temperature anneal was found to reduce the CTI by
$\sim 1.5$ which is finite but was deemed to not be substantial enough to justify an on-orbit
bake in-flight. Hopkinson noted that in future studies, it would be useful to perform both a room-temperature and a cryogenic irradiation to bound the radiation response (Hopkinson and Mohammadzadeh 2006, Hopkinson et al. 2009).

Given the large number of devices on the focal plane, as well as the number of device variants, it is no surprise that many different CCDs were manufactured and tested at different stages of the mission development. There is a chance for changes and subtleties in the manufacturing process to have led to different performance results from different devices. A challenge of the pre-flight tests was to work out which properties were inherent to the CCD devices and not related to the manufacturing. For the most part, no significant discrepancies were found between different devices. Interestingly, Hopkinson found that the $1500 \ \Omega \text{cm}$ and the $100 \ \Omega \text{cm}$ devices had similar defect inventories despite the device variant differences (Hopkinson and Mohammadzadeh 2006).

In a particular pre-flight study, it was found that a rejected flight-model device had a smaller than expected SBC FWC in half the device (Kohley et al. 2009). This prompted further investigations, upon which it was revealed that CCDs manufactured after 2004 had a greater likelihood for having SBCs with reduced FWCs. This was thought to be related to a change in the photo-lithographic mask used by e2v but this was noted to be circumstantial (Seabroke et al. 2013b). More details of the reduced SBC FWC is given in Chapter 5.

Given the timescale of device manufacturing and testing, the final devices integrated on the focal plane were all manufactured at different times. The SBC FWC results set a precedent for interesting behaviour seen in the CCDs to be linked to their corresponding year of manufacture. Figure 4.2 details the year of manufacture for all the devices which is used to compare against different results obtained in this thesis.

### 4.2.3 Computational models

The approach taken during the development of Gaia’s computational models, was to start as complex and as accurate as possible with microscopic models. These models would be able to simulate effects down to the sub-electron level. Once these effects were well understood and modelled reliably with respect to experimental data, simplified macroscopic models could be developed which would reduce the computational cost whilst maintaining accuracy (Seabroke et al. 2008).
Fig. 4.2  The year of manufacture of the in-flight CCDs installed on the Gaia focal plane.

Microscopic models were developed and used extensively to understand experimental results and obtain solutions that could help build the macroscopic model. In addition to this, these models could be used to provide information on measurements that would not be reproducible in the laboratory, such as the CTI effects on very faint end measurements. George Seabroke, who at the time was a researcher at the Centre for Electronic Imaging at the Open University, developed a number of microscopic models to model the radiation damage effects on the Gaia CCDs. Seabroke benchmarked Silvaco ATLAS semiconductor model simulations of the Gaia pixels against other microscopic CCD models as well as against experimental data. Seabroke found that signal packets needed to be described with density-volume models rather than previously used volume driven models to explain observed effects in the Gaia CCDs such as the effects of optical background. The Silvaco models were used to work out the performance limits at the bright and faint end measurements of Gaia’s instruments. Seabroke was also able to accurately model the effects of the Supplementary Buried Channel and found doping widths that could explain the experimental results of the reduced Full Well Capacities of the SBCs. It was found that the reduced SBC FWCs found in some of the experimental work was most likely due to uncalibrated systematic offsets in the photolithography of
the devices (Seabroke et al. 2008, 2009, 2010).

A primary motivation for the development of the Gaia Silvaco Pixel model was to obtain the electron densities of signals as a function of position within the pixel as well as a function of the number of constituent electrons. These results were used in the development of another microscopic model called CTI effects model for Gaia (CEMGA) to calculate the number of radiation-induced trap defects that would be encountered by a charge packet as well as the probability of capture. CEMGA was a microscopic Monte-Carlo model developed by Thibaut Prod'homme, at the time, a researcher at Leiden University, to simulate the charge transfer effects of the Gaia CCDs without the use of the semiconductor simulations used in George Seabroke’s work. The model was developed in such a way that it could be used in other missions and CCDs. This model was also used to quantitatively measure the impact of radiation damage effects. The CEMGA model was able to accurately replicate experimental data, verifying its legitimacy. The model was used to quantify the biases that would have arisen from radiation damage; these were calculated at the range of magnitude levels that would have been observed by Gaia. More details of this work and the model can be found in Prod’homme (2011).

The simulations and results from CEMGA were used to help develop a macroscopic model called the Gaia Charge Distortion Model (CDM) (Short et al. 2013). CDM was designed to calibrate out the radiation-induced bias on the measurements by forward-modelling the charge distortion to the CCD images at the CCD sample level. A forward-modelling approach was chosen to preserve the noise properties of the data as well as to retain the flexibility of treating dispersed spectra and non-point source objects in the same way as isolated stars. Compared to more complex Monte-Carlo models like CEMGA, CDM was designed for fast implementation in the data processing pipeline while still being realistic and flexible enough to accurately reproduce the CTI distortion. By using more accurate models such as CEMGA as a basis, it was possible to obtain and calibrate relatively accurate results with CDM. CDM was designed to be used iteratively, where the model parameters would be constantly adjusted to distort the charge data until the resultant target data best matched a set of real data. Primarily developed by Alex Short, this model was found to accurately replicate effects in the experimental data as well (Short et al. 2013).
Throughout the development of all the models, investigations were made with respect to the density-volume relationship of the electron signals. In Gaia’s early models, it was initially assumed that electron signals would mostly be volume driven where a larger number of electrons would occupy a larger space. However, as mentioned previously, Seabroke et al. (2008) found that a small level of optical background, not more than 5 electrons, was found to be sufficient to occupy and fill a disproportionate number of slow-release traps. The Silvaco models have revealed that in reality, the true behaviour is a hybrid between a density and volume driven approach. In CDM this behaviour is modelled with equation 4.1.

\[
\frac{V_c}{V_g} = \left( \frac{N_e}{FWC} \right)^\beta
\]  

(4.1)

In equation 4.1, \(V_c\) is the confinement volume occupied by the signal, \(V_g\) is the geometric volume of the pixel, \(N_e\) is the number of electrons of the signal, \(FWC\) is the total number of electrons occupied at the Full Well Capacity and \(\beta\) is a parameter that details how volume or density driven the model is. A \(\beta\) parameter of 0 would mean the model is entirely density driven where the density of the signal increases with the signal size but the volume remains constant. Conversely, a \(\beta\) parameter of 1 means the model is volume driven and the volume of the charge packet increases with the signal, but the density stays constant.

Alongside the development of Gaia’s instruments and models, a software system known as the Astrometric Global Iterative Solution (AGIS) was developed by DPAC. AGIS was developed as a crucial part of Gaia’s scientific data processing to solve for the astrometric parameters of the objects observed by Gaia. This was realised to be a computationally expensive problem and an iterative approach was devised where the observations themselves would form the basis of the astrometry solution; this makes AGIS a self-calibrating solution. As part of its design, AGIS is divided into distinct processing blocks, each of which deals with features such as object source, attitude, calibration, and global updating. The solution is central to the data processing and performance of the Gaia mission as a whole, providing astrometric results with the reference frame and geometric calibration of the instruments (Lindegren et al. 2012).
4.3 Post-launch results

4.3.1 General performance

After years of development and testing, the Gaia spacecraft was successfully launched on 19th December 2013. After a 6-month in-flight commissioning phase, it began full mission operations. While some issues have arisen between the time of launch to the writing of this thesis, such as high straylight levels, water contamination, and variations in the basic angle (Prusti et al. 2016), solutions were found and have allowed Gaia to operate and collect data. At the time of writing of this thesis, three major data releases had been publicly released, with a wealth of astrometric, photometric, and spectroscopic measurements of all the objects observed by Gaia. The mission has gone beyond its nominal mission lifetime of 5 years and is now only limited by the on-board micro-propulsion fuel; the current mission extension is until the end of 2025. Further details of the Gaia mission and all the data available can be found at https://www.cosmos.esa.int/web/gaia/home.

A major factor for Gaia’s exemplary mission performance has been the low level of radiation-induced CTI that was measured from the devices. While most of the spacecraft’s time is spent on taking astronomy measurements, periodic activities are run in-flight to check the operations of the all the instruments. In some of these activities, Virtual Objects (VOs) are produced by inserting artificial detections into the on-board computers to obtain information to monitor features like straylight, transient events and more. As outlined in Chapter 3, regular CIs are also carried out on the AF, BP and RP instruments to mitigate the effects of CTI. The CTI measurements from these CIs, as well as from the VOs obtained during special calibration sequences, can allow for the study of the in-flight CTI behaviour and its evolution in time.

Analysis of the CTI from the in-flight CIs has revealed that the increase in CTI with time has been lower than what was expected from the pre-flight on-ground tests. When extrapolating the CTI measured in 2016 to the End of Mission (EoM) and removing the 20% safety factor from the on-ground irradiations, it was found that Gaia was on track to accumulate $\sim 7 - 8$ times less radiation-induced CTI compared to the on-ground tests; this is nearly an order of magnitude less than what was predicted (Crowley et al. 2016a,b, Crowley 2016c). The lower levels of CTI have also meant that CDM has not
been required in the data processing chain; AGIS has been sufficient to calibrate out any systematic biases (Crowley 2020). While this is beneficial for the science objectives of the mission, it is important to understand, as well as possible, why this discrepancy has occurred between the pre-flight tests and predictions and the in-flight data. This is to verify the reliability in the pre-flight testing as well as to obtain a better overall understanding of what is going on which can positively feedback into other missions and studies.

4.3.2 Reasons for CTI discrepancy

A number of different reasons have been proposed that could have led to the measured lower-than-expected CTI levels; these are all outlined below.

**Straylight:** From in-flight measurements, it was discovered that there were unexpected and significant levels of straylight on the focal plane. The origin of the straylight was identified as being from two different sources; the diffraction of solar light around the sunshield and light from off-axis astrophysical sources. While straylight adds photon noise to the measurements which can negatively affect the results, it can also fill the trap defects. If the trap defects are filled then the signals can get transferred without any loss of electrons from the charge packet. This CTI mitigating effect was noted in the pre-flight on-ground tests and is most likely occurring in-flight.

**Irradiation Temperature:** In the Gaia radiation damage studies, as well as the studies for previous space missions, most irradiations were performed at room-temperature. Relatively more recent studies have revealed that cryogenic irradiations, performed at temperatures more reflective of the interstellar environment, lead to the formation of alternate trap defects as compared to room-temperature irradiations. This is likely because the stability of trap defects varies with temperature. While room-temperature irradiations were the standard practise for previous missions, the need for more precise and finer measurements with each generation of missions means that room-temperature irradiations will no longer be sufficient to accurately predict and quantify in-flight radiation damage. It is likely that the cryogenic irradiation environment will lead to the formation of alternate trap landscapes which would lead to different CTI measurements compared to those from room-temperature on-ground irradiations.

**Operation Temperature:** It was believed that the operating temperature of the
devices may have caused CTI differences given that the behaviour of trap defects is temperature dependent. Gaia’s operating temperature was chosen to be 163.15 K as a balance between the parallel and serial CTI. The on-ground tests and measurements were known to have been carried out at 163 K. Temperature measurements from sensors on the focal plane have revealed that it has been relatively stable at 163.15 K. Though some heating events were conducted in-flight to de-ice the focal plane, the temperature increase was not significant enough to thermally anneal the trap defects. Annealing is the phenomenon where, if the temperature of a device is increased, trap defects are able to reach their activation energy which leads to an irreversible change in the trap landscape; this usually leads to a subsequent drop in the CTI level.

**Radiation Environment:** The two primary sources of radiation in space are the solar wind and galactic cosmic rays (GCRs) which both comprise of charged particles, primarily protons, alpha particles and electrons, with a smaller number of heavier ions. GCRs are generally more energetic and the proton flux peaks at higher energies as compared to protons in the solar wind. As mentioned in the previous section, the predicted NIEL dose for the CCDs of the focal plane only considered the effects of solar protons and neglected the contribution of GCRs. This was based on the predicted level of solar activity that was made at the time. Closer to the launch date and after Gaia was launched, measurements of the solar activity have indicated that the Sun has not been as active as what was initially predicted and there have been fewer Earth-directed solar events. As GCRs have an inverse relationship with solar protons, this means that there has also been a non-negligible contribution of radiation damage from GCRs. Overall, it is likely that the lower activity of the Sun has been a big factor in the lower in-flight CTI measurements.

**Particle Fluence:** To reproduce the accumulated radiation damage over the course of the mission, CCDs are often irradiated with a large dose of high-energy particles on a timescale of a few minutes. While this procedure is quick at getting results, it is certainly not representative of the actual activity experienced by Gaia and could be causing a different level of damage than would be observed by the spacecraft. There is a chance that exposing the CCD to the same amount of radiation over a longer period of time would produce different results, distinct from the results of irradiating a mission’s worth of radiation in a short time. The total amount of energy that can be transferred to
the primary knock on atom increases with proton energy and there is a greater likelihood for clusters of defects to form as opposed to point defects. As previously mentioned, the contribution of the GCR flux to Gaia’s in-flight CTI is finite. The average energy of the particles in GCRs is known to be higher than that of solar protons. Overall, it is likely that the difference in particle fluxes between in-flight and on-ground have led to some non-intuitive differences in the observed CTI effects.

From previous studies, the straylight factor was quantified and found to have a contribution that was finite but not large enough to explain the disparity. The previous studies also concluded that the lower levels of solar activity were largely responsible for the disparity between the in-flight and on-ground CTI. In this thesis, this disparity between the CTI levels is studied further and different factors affecting the CTI differences are quantified. Given the difference between the pre-flight on-ground and in-flight CTI, as well as the factors that could influence CTI measurements, equation 4.2 is made where the collective product of all the factors should lead to the $7 - 8$ factor difference between the in-flight and on-ground CTI.

$$CTI_{ground} = CTI_{flight} \times f_{straylight} \times f_{cryogenic} \times f_{dose} \times f_{other}$$  \hspace{1cm} (4.2)

In equation 4.2, the impact of the GCRs, the radiation environment and the particle fluence are all combined into a singular $f_{dose}$ factor. Equation 4.2 only contains the factors that were studied in this thesis, the remaining factors are combined into the $f_{other}$ term.

### 4.4 Conclusions

The main insights and results from the pre-flight Gaia radiation damage studies have been outlined and discussed extensively in this chapter. A number of details were revealed with respect to the impact of the radiation on Gaia’s CCDs from both experimental tests and computer models developed during the development of the mission. All of the results were documented and recorded to ensure the mission’s success and longevity as well as to identify areas of investigation for future missions and studies. In-flight measurements after Gaia’s launch have revealed that the in-flight CTI levels were much lower than what was measured and predicted from the on-ground tests. This
disparity leads to the crux of this thesis’s goal; to quantify the factors responsible for this disparity as accurately as possible. Chapters 5 and 6 detail the analysis of more in-flight CTI data while chapters 7, 8 and 9 detail and quantify the straylight, radiation dose and irradiation temperature factors on CTI, as accurately as possible within the limits of this thesis’s research.
CHAPTER 5

Early mission in-flight CTI - RVS Case Study

5.1 Introduction

To begin the investigation of the radiation damage experienced by the CCDs of the Gaia focal plane, analysis was performed of specific charge calibration data to measure the in-flight charge transfer inefficiency (CTI). This analysis was performed with data that was taken towards the end of the in-flight commissioning phase with the Radial Velocity Spectrometer (RVS) CCDs; it was obtained with the objective of understanding the radiation damage state of these CCDs. Some specific objectives of this data were to characterise and track the amount of CTI in different CCD columns as well as to measure the Full Well Capacities (FWC) of the Supplementary Buried Channel (SBC) (Seabroke et al. 2013a). It would be useful to characterise the RVS CCDs before regular operations as routine CIs would not be implemented on the RVS CCDs. As the data was obtained only five months after the spacecraft was launched, large CTI effects were not expected to be measured in this dataset.

Given that the majority of the RVS spectra will be observed towards the faint end of the magnitude range, this means that it is likely the charge packets will contain fewer electrons than the capacity of the Supplementary Buried Channels. However, some of the CCDs are likely to have reduced SBC full well capacities, as discussed in chapter 4. This means the signals in these CCDs would not be confined to small volumes as expected and instead would consequently encounter more traps and experience more trapping (Kohley et al. 2009, Seabroke et al. 2013b). The CI levels were chosen to be as representative as possible of the majority of the RVS charge packet levels. It was thought that by using a CI level of less than 1000 electrons, it would be possible to identify the CCDs that had reduced SBC Full Well Capacities.
This chapter details the processing and analysis of this in-flight calibration data. A number of interesting features and behaviour were realised in this analysis which can form the basis of future investigations and studies for other spacecraft. While no significant results were obtained with respect to radiation damage in the Gaia CCDs themselves, the methods and techniques used here were implemented in the analysis of other datasets.

5.2 Data outline

As mentioned previously, the charge calibration data was collected at two different CI levels. One was to represent signals characteristic of the RVS CCDs and to measure the SBC capacity as best as possible. The other signal level was chosen to be around $\sim 19,000e-/pixel$ which should be the same as the CI baseline for the AF and XP devices. The motivation behind this was to initialise CDM parameters of every column for future data processing and analysis (Seabroke et al. 2013a).

The CIs were run for a duration of 60 TDI lines; this was a longer duration than Radiation Campaign 3 where a duration of 20 TDI lines was used. The CI profiles were chosen so that enough information would be present to perform complete data analysis. It was determined that in addition to the 60 TDI lines of CI, the profiles needed to have enough pixels to contain the charge release trail as well as including pixel samples before the CI and after the release trail to measure the background. From the RCs, it was found that the charge release trails from a 20ke-/pixel CI with an end-of-mission irradiation, would become sub-electron after 600 TDI from the CI. From these results, combined with results from other RC studies, a CI period of 630 TDI was chosen in order to measure trails from defects with long emission time constants (although it was noted to be very unlikely to measure such signatures this early in the mission) (Seabroke et al. 2013a).

The number of CIs was chosen based on the aim to measure trails between 1-60 electrons and to have sufficient repeat measurements to reduce the noise below a level of 4.8 electrons. This was the worst-case noise detection level after considering HR sampling noise from a performance test as well as noise from the sky background and straylight from the BAM laser. The CI profiles used in this data scheme had 10 AC pixels; given that each CCD has 1966 Across-Scan (AC) columns, the CI scheme was
designed in a way to sample, analyse and investigate every AC position, as detailed in Figure 5.1 (Seabroke et al. 2013a).

**Fig. 5.1** A schematic of the proposed RVS CI scheme as planned. Each blue box represents one RVS class 0 virtual object (VO) i.e. 1260 AL pixels by 10 AC pixels with each VO containing two bands of CIs, 60 TDI lines long (Seabroke et al. 2013a).

### 5.3 Data processing

Once the charge calibration data was obtained, it needed to be processed before any results could be extracted from it. The data processing task itself revealed peculiarities in the data that are noted here for future studies and investigations. The data files had varying amounts of straylight whose effects needed to be removed for accurate results. This was done by calculating the straylight level for each data file as the median signal level of each data file. The data files were then split by their measured straylight levels (to the closest integer value) and these straylight levels were subtracted from the data files.

The charge injections were noted to be highly variable across the pixels in the parallel, ALong-scan (AL) directions. In some cases, particularly for the larger CI levels, a “droop” was also seen where the CI level would decrease from TDI line to TDI line for the continuous CI; this effect was also noted in the RCs (Seabroke et al. 2013a). For
the data analysis, any files which had a significant amount of CI droop (> 1%) were neglected. This was possible due to the large amount of data available, but this will not always be feasible. The CI droop is therefore something that should be accounted for and studied in future investigations. The mean CI level across the 60 TDI lines was taken as the signal level to be used in the data analysis, rounded to the nearest integer value. Figure 5.2 details the CI profiles for 10 CIs, taken from a single data file, which illustrates a very small amount of trailing charge, non-uniformity in the charge injections as well as noise in the data.

Fig. 5.2 Ten different charge injections (CI) from a data file from the RVS charge injection scheme. The exact signal level varies per pixel for each average CI level on account of noise.

5.4 CTI results

5.4.1 EPER and FPR

To calculate charge transfer inefficiency in CCD charge data, two different CTI measurement techniques are predominantly used, as described by Janesick (2001). These are the First Pixel Response (FPR) and the Extended Pixel Response (EPER). First Pixel Response (FPR) involves exposing the CCD to a flat-field illumination after which half the charge is clocked out, creating a leading edge with the remaining charge. The rest of the charge is then transferred through the flushed region and charge is captured and
lost from the leading edge of the signal from empty trap defects. This charge lost from
the leading edge, $S_L$ (e-) is used to calculate the CTI, as detailed in equation 5.1

$$CTI_{FPR} = \frac{S_L}{S \times N_p} \quad (5.1)$$

In equation 5.1, $S$ (e-) is the signal of the flat-field illumination and $N_p$ is the num-
ber of pixel transfers across the CCD (in the AC direction for serial CTI and the AL
direction for parallel CTI). FPR probes charge capture from all the empty traps encoun-
tered by the signal, regardless of their emission time constant and is a good indicator of
the density of trap defects present. If the trap density is high enough, charge loss can
also be experienced by each successive pixel after the first pixel, although to a lesser
degree, as has been noted on the Gaia CCDs (Crowley et al. 2016b).

Calculating the EPER CTI also involves exposing the CCD to a flat-field exposure
which is then read out of the device along with a region of parallel or serial overscan.
A fraction of the charge will be captured by the traps and re-emitted into the overscan
region when the original charge packet has passed through. This leads to the formation
of a charge tail, trailing behind the signal in the serial and parallel directions, depending
on the direction of transfer, whose internal charge can be summed and used to calculate
the CTI through equation 5.2.

$$CTI_{EPER} = \frac{S_D}{S \times N_p} \quad (5.2)$$

In equation 5.2, $S_D$ (e-) is the total deferred charge measured in the pixel region, $S$
(e-) is the signal level and $N_p$ is the number of pixel transfers. The length of the charge
tails can be influenced by the transfer speed and temperature of the device as well as the
trap densities and emission time constants of the trap defects. To a degree, the number of
pixels used to calculate the deferred, trailing charge can influence the EPER CTI value.
In general, EPER calculations generally give lower CTI measurements as compared to
FPR which is able to probe almost all traps, regardless of their emission time constant.
EPER measurements are still useful as they probe CTI from charge emission and the
tails can be used to characterise the different trap species present in the data.

Due to the limitations of Gaia’s in-flight capabilities, several different transfer times
cannot be probed, nor can a flat-field illumination be conducted. The charge injections
are able to fulfill the same objectives as the flat-field, however all the CTI measurements will be representative of the TDI clocking speed (in the AL direction) and the serial transfer speed (in the AC direction). The EPER and FPR CTI measurement techniques were used in the analysis of other datasets described in this thesis. For the analysis in this chapter, a slightly different CTI measurement technique was used, as an adaptation of the EPER CTI measurement technique, in order to try and identify the presence of an SBC.

5.4.2 Supplementary Buried Channel

The Gaia CCDs were designed with a Supplementary Buried Channel in order to reduce the CTI of the measurements. The function of the SBC was to confine charge to a smaller volume as compared to the main buried channel. This would mean that the number of effective traps for signals and charge injection levels below the SBC capacity should be relatively smaller assuming a uniform distribution of traps through the buried channel; this results in less charge loss and lower CTI. This can be seen as a discontinuity in CTI measurements with respect to signal level, where the CTI increases at higher trap densities when charge begins to spill into the main buried channel (Seabroke et al. 2013b).

In selected pre-flight studies, a number of Gaia CCDs manufactured after 2004 were found to have reduced SBC FWCs in the upper half of the CCDs. This was thought to be related to e2v changing their photo-lithographic mask set in 2004, although this is noted to be circumstantial. Photo-lithographic masks are used when implanting the doping that is used to define each pixel feature. Small positioning variations during the photolithographic process of the stitching blocks of the devices were found to lead to small lateral displacements of stitching blocks in the upper half of the detector as compared to the lower half over the single stitching boundary in the along-scan direction (Kohley et al. 2009, Seabroke et al. 2013b).

From analysis of charge trapping in both halves of certain on-ground CCDs, it was found that the SBC FWC in the lower half of these CCDs was $\sim 1000 - 3000$ electrons. By contrast, the reduced SBC FWC in the upper half of these devices was only $\sim 50$ electrons (Kohley et al. 2009, Seabroke et al. 2013b). By the time this was realised, it was too late to change the in-flight devices or measure the SBC FWCs onboard the
spacecraft before launch, given that all the in-flight devices were manufactured post-2004. Most of the the faint star \(13 \leq G \leq 20\) mag) astrometric predictions were made assuming a non-reduced SBC FWC (Holl et al. 2012, Prod’homme et al. 2012). Hence, an objective of this charge calibration data was to try and identify which RVS CCDs would have a working or a reduced SBC FWC for accurate data modelling in the data processing pipeline.

As the SBC confines signals to a smaller volume, it is necessary to simulate the behaviour of the signals’ charge cloud while it is restricted to the SBC in order to investigate it. Introduced in chapter 4 and implemented in CDM, equation 4.1 describes how much of the charge cloud model is volume driven or density driven. When the \(\beta\) parameter is closer to zero, trapping is more density driven where the electron density increases as the signal charge gets larger. When the \(\beta\) parameter is closer to one, density is more constant and trapping is driven by the interaction volume of the electrons with the traps (Short et al. 2013). Given the confinement of charge to a small volume in the SBC, the SBC would likely change any fitted values of \(\beta\).

Taking and combining elements of equation 5.2 with equation 4.1 returns equation 5.3 which was used to investigate the presence of an SBC.

\[
S_D = A \times S^\kappa
\]  

In equation 5.3, \(S_D\) (e-) is the total deferred charge, \(S\) (e-) is the signal level, \(A\) is a normalisation constant and \(\kappa\) is a power term that is analogous with \(\beta\) from equation 4.1. To explain equation 5.3, it is assumed that if the charge signal encountered a larger number of traps, then the total deferred charge would be larger which would mean that a larger value of \(\kappa\) would be fitted to the data. Conversely, if the value of \(\kappa\) is relatively smaller, then this would imply that fewer traps would have been encountered by the signal which would likely indicate the presence of an SBC.

To justify the use of equation 5.3 in the context of SBCs, Figure 14 from Seabroke et al. (2013b) is replicated in Figure 5.3 with equation 5.3 fitted onto the graphs in different signal regimes. A larger amount of traps would lead to a larger amount of trailing deferred charge due to a larger amount of emission. Hence, equation 5.3 can be fitted onto the data of Figure 5.3 even though the original data was looking at the number of traps per signal level as opposed to the amount of deferred charge. The
smaller number of traps inside the SBC leads to a smaller fitted value of $\kappa$ inside the SBC as opposed to the data outside of the SBC. Figure 5.3 also highlights the different FWCs between the two halves of the CCDs; approximately 50 electrons for a reduced SBC and almost three thousand electrons for a non-reduced one.

![Graph](image)

**Fig. 5.3** Replication of the plots from Figure 14 of Seabroke et al. (2013b) of the number of detected radiation traps as a function of signal level for a post-2004 manufactured irradiated CCD. (a) The number of traps in the lower half of the CCD. (b) The number of traps in the upper half of the CCD. Fits of equation 5.3 are added to highlight the trends in the behaviour for different signal ranges.

Given the use of equation 5.3 in Figure 5.3 to identify an SBC, a similar approach is taken with the RVS charge calibration data. For the data processing, the datafiles
were filtered by the background level and split by each different RVS CCD to produce Figure 5.4 which details the deferred charge with respect to the charge injection level for each CCD. The charge injections were rounded to the nearest integer value and three trailing pixels after the charge injections were used to calculate the deferred charge. Three pixels were chosen because for most of the data used here, the charge tails did not extend beyond one or two pixels. Given the large volume of data available, a heatmap was produced, as detailed in Figure 5.4. As described previously, the data falls into two distinct groups, one with smaller sized CI levels less than 3000 electrons and the other at larger levels from around 16,500 to 22,500 electrons. Table 5.1 details the fits of the parameters of equation 5.3 made for each CCD in the two CI level groups.

![Image of Figure 5.4](image.png)

**Fig. 5.4** The deferred charge against charge injection level for all 12 RVS CCDs. In this set of results, the background straylight was kept fixed at a value of 5 electrons per pixel.

From the results of Table 5.1, it is difficult to extrapolate a relationship for the fitted values of the parameters of equation 5.3 for the two different signal groups. One factor affecting the results, as observed from Figure 5.4, is that different RVS CCDs measure different amounts of CTI, and by extension, deferred charge. This is likely due
Table 5.1 The fitted parameters for $A$ and $\kappa$ from equation 5.3 for each of the RVS CCDs, split between the low and high CI levels.

<table>
<thead>
<tr>
<th>Strip</th>
<th>Row</th>
<th>Low CI $A$</th>
<th>$\kappa$</th>
<th>High CI $A$</th>
<th>$\kappa$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>3.21 ± 0.05</td>
<td>0.257 ± 0.003</td>
<td>0.32 ± 0.02</td>
<td>0.540 ± 0.006</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.39 ± 0.01</td>
<td>0.396 ± 0.001</td>
<td>2.1 ± 0.1</td>
<td>0.355 ± 0.006</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.18 ± 0.01</td>
<td>0.449 ± 0.001</td>
<td>2.4 ± 0.5</td>
<td>0.35 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.01 ± 0.04</td>
<td>0.336 ± 0.003</td>
<td>1.69 ± 0.08</td>
<td>0.377 ± 0.005</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>0.52 ± 0.01</td>
<td>0.596 ± 0.003</td>
<td>8.0 ± 0.3</td>
<td>0.262 ± 0.003</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>4.7 ± 0.1</td>
<td>0.100 ± 0.003</td>
<td>17 ± 2</td>
<td>0.00 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>5</td>
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<td>0.193 ± 0.002</td>
<td>2.9 ± 0.4</td>
<td>0.18 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.714 ± 0.008</td>
<td>0.506 ± 0.001</td>
<td>25 ± 2</td>
<td>0.11 ± 0.01</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>2.14 ± 0.02</td>
<td>0.445 ± 0.001</td>
<td>6.5 ± 0.2</td>
<td>0.305 ± 0.003</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>3.63 ± 0.08</td>
<td>0.153 ± 0.003</td>
<td>0.34 ± 0.05</td>
<td>0.41 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.49 ± 0.02</td>
<td>0.411 ± 0.002</td>
<td>12.8 ± 0.7</td>
<td>0.176 ± 0.005</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3.55 ± 0.03</td>
<td>0.251 ± 0.001</td>
<td>14.2 ± 0.5</td>
<td>0.164 ± 0.004</td>
</tr>
</tbody>
</table>

to different pre-flight trap defect landscapes. It is therefore difficult to disentangle the effects of the alternate trap landscapes from potential SBC effects. The split of the CI data into two groups of higher and lower levels also makes it difficult to determine the FWC of the SBCs. For a normal SBC, the FWC is around 2850 electrons; however, this is also the approximate upper limit of the lower CI levels in this dataset. This makes it difficult to look for any changes in the behaviour once the signal is outside the SBC. Some of the CCDs (RVS2, Row 7 and RVS3, Row 7) do seem to show a slight “kink” in the deferred charge once the CI goes past a signal level of around 1000 electrons. However, it is difficult to ascertain whether this is due to a working SBC without more data between the two groups of CI levels.

At the large charge injections, the signal is almost entirely outside the SBC, so the SBC effects were not easily seen. Another issue is that the reduced SBC FWC was measured to be around just 50 electrons from previous studies. This is a difficult signal level to probe and some of the CCDs in Figure 5.4 do not even have CIs around this level. This makes it harder to identify the presence of an SBC and to measure its capacity.

While it is unfortunate that SBC FWC measurements could not be reliably made with this dataset, a number of insights have been made for future studies. For example, to more reliably measure and identify the SBC, other methods of trap-defect inves-
tigation such as “trap-pumping” should be conducted. Trap-pumping is an analysis technique where a flat-field signal is clocked between CCD phases in order to produce dipoles at the trap defect locations. This analysis technique makes it possible to observe individual trap species and their properties to a high level of accuracy (Hall et al. 2014, Wood et al. 2014, Murray et al. 2013). The pre-flight studies that initially investigated the SBCs of the Gaia CCDs used pocket-pumping to identify the differences between the upper and lower halves of the CCDs (Kohley et al. 2009).

If trap-pumping is not possible, such as with Gaia, the next best option would be to perform CIs at a larger range of signal levels as opposed to only have CIs at two levels. This would allow a trend in the behaviour of deferred charge or CTI across different signals to be observed and used to identify the presence of an SBC, as has been done in previous studies (Seabroke et al. 2013b, Crowley et al. 2016b). A limitation with this data is that there is little data at higher signal levels, which causes “flatter” fits of equation 5.3 at the high CI levels, leading to lower fitted values of $\kappa$ as compared to the fitted values at the low CI levels as detailed in Table 5.1.

To conclude this analysis, it should be emphasized that SBC FWCs were never an officially agreed-upon acceptance criterion for CCDs in the contract between ESA/EADS-Astrium and e2v, but were instead a design goal. This is a primary reason for why the specifics of the SBCs were not systematically tested in the Gaia development phase. It is a challenge to test large quantities of CCDs to identify unexpected design and performance issues. While the discovery came too late to implement design changes in Gaia, the results do provide useful feedback for the development and testing of future space missions. For example, while it was decided to not implement an SBC on the CCDs of the Euclid spacecraft, SBCs have been implemented on the CCDs of the SMILE mission, after more analysis of their effects (Seabroke et al. 2013b, Soman et al. 2018).

5.4.3 Year of manufacture comparison

As mentioned in the previous section and observed in Figure 5.4, different RVS CCDs appear to demonstrate different degrees of CTI. For the next set of results, the CTI of the individual CCDs was calculated and analysed at a fixed signal level; this would allow for a more reliable comparison of the CTI between different devices. This time,
the data were filtered by fixed charge injection levels in addition to the straylight level, with both levels averaged to the nearest integer value.

The deferred charge was calculated for each CCD, again using three trailing pixels. Figure 5.5(a) is produced which highlights the deferred charge of each different RVS CCD as laid out on the focal plane at a given signal level. This set of results is analogous to EPER CTI measurements; the reason EPER was not calculated directly was to reduce the uncertainties given the large amount of data and noise present in the measurements.

![Figure 5.5](image)

**Fig. 5.5** (a) The amount of deferred charge in the three pixels trailing the charge injections (CI) for each RVS CCD. In this figure, data was used that was filtered at a CI of ∼17,500 electrons and a background straylight level of 5 electrons. (b) The year of manufacture of the in-flight RVS devices, as detailed from Figure 4.2.

From the CTI distribution pattern of the RVS devices in Figure 5.5(a), it is observed that different CCDs do indeed measure different levels of CTI for a given signal level. This would indicate that each of the CCDs has a significantly different pre-flight trap defect landscape. The CTI distribution pattern is identical to the pattern from a different pre-launch CTI analysis of the in-flight devices (Crowley 2016c). This verifies the analysis technique of using deferred charge as a measurement of CTI and indicates that no significant amount of radiation had occurred after a few months of orbit.

Figure 5.5(b) illustrates the year of manufacture of the RVS CCDs, as originally detailed in Figure 4.2 from Chapter 4. When comparing the two figures of Figure 5.5, it
is noted that the RVS devices that were manufactured in 2009 measured larger amounts of CTI as compared to the devices that were manufactured in earlier years. This CTI difference is up to an order of magnitude higher for the 2009 devices. It is most likely that the CTI differences are due to defects that were formed during manufacturing. It is currently unknown what changed in 2009 to form devices with a higher initial CTI.

The difference in pre-flight trap defects is suspected to be due to a higher number of impurities at the time but the exact reasons are likely subject to licensing and non-disclosure agreements between different companies and institutes involved in the Gaia mission and the CCD manufacturing process. In the future, a technique like “trap-pumping” could be applied to not only identify the manufacturing defects but also to measure their trap densities. This would be useful for the verification and testing of devices for other missions as well as in revealing more insights into the nature of CCDs and CTI.

5.5 Conclusions

Previous on-ground and in-flight studies have either analysed individual CCDs separately or have predominantly focused on the analysis of the AF variant CCDs. CTI analysis of the thicker RP CCDs has been relatively more limited in depth and detail. In this chapter, early mission in-flight data from the RP devices on the RVS instrument was analysed and the CTI of these device variants has been studied to a greater level of detail as compared to previous work. A link between the the initial CTI levels and the year of manufacture of the devices has also been established where devices manufactured in 2009 were found to have higher levels of CTI.

This chapter has presented an overview and analysis of charge calibration data that was taken during the in-flight commissioning phase. An objective of taking this data was to try and measure the SBC FWCs of the RVS devices, which, unfortunately, was not possible due to uncertainty in the measurements. For future space missions, it is recommended to either perform trap-pumping or have a charge injection scheme at a larger range of signal levels in order to more reliably identify the presence of an SBC and measure its capacity.

The CTI analysis performed with this dataset has not revealed any significant deviations from the pre-launch results and demonstrates that no major solar events took place
during the commissioning phase. As mentioned previously, the CTI analysis did reveal that devices manufactured in 2009 measured larger amounts of CTI as compared to the other devices. For future studies, it is recommended to test, measure and characterise all the in-flight devices as accurately and precisely as possible. Any irregularities should immediately be noted and compared with either manufacturing techniques or results from other devices, so the CTI and its evolution can be reliably tracked for performance metrics.

While there were not many novel results from the analysis of this particular dataset, the work in this chapter acts as a precursor to data analysis techniques used to analyse alternate Gaia charge calibration data. The techniques and ideas used here are developed and implemented in the analysis of other datasets, predominantly in Chapter 6.
CHAPTER 6

In-flight parallel and serial CTI in time

6.1 Introduction

Having analysed a set of in-flight charge calibration data from the previous chapter, this chapter uses and builds upon the knowledge and data analysis techniques from chapter 5 to perform further analysis on additional in-flight data. Whilst chapter 5 was only concerned with the analysis of early mission charge calibration data from a few months into the mission, this chapter is focused on the analysis of data taken over a much longer period of time. Results are obtained for the charge transfer inefficiency (CTI) at different stages of the mission across all the scientific instruments on the focal plane. Comparisons are also made with the NIEL dose prediction from Figure 4.1 of Chapter 4; re-introduced here as Figure 6.1. New results and insights are revealed about the CTI and its evolution in time for the different CCD variants across a six-year period (72 months). These results are used in later chapters to compare with on-ground data and to quantify different factors impacting the CTI.

6.2 Detector performance monitoring strategies

Due to Gaia’s continuous time-delayed integration (TDI) operation, the detector system does not have a built-in shutter or an on-board lamp, as these would interfere too much with the measurements. This means that standard detector calibration activities that have been performed in other space missions, such as the Hubble Space Telescope (HST), cannot be conducted. These calibration activities include dark image acquisitions, gain charge monitoring, and performing flat-field illuminations with a lamp. Some of these effects can be calibrated out using the actual science data contained within the global iterative solution (Lindegren et al. 2012). Other detector parame-
In-flight measurements and a number of strategies and special calibration activities are implemented and run periodically in-flight to monitor operations and characterise the electronics and devices (Crowley et al. 2016a).

For some of these calibration activities, the nominal operation for the CCDs needs to be stopped such that Virtual Objects (VOs) can be strategically placed to correctly sample each CCD. These VOs are acquired by inserting artificial detections into the algorithms to propagate a virtual stellar object across the focal plane. They are unique windows which are allocated different sizes and locations on the CCDs; they are designated a lower priority compared to astronomical objects and are used for calibration measurements. These windows can be analysed to provide information about straylight levels, defect column evolution, electronic offset levels and CTI evolution (Crowley et al. 2016a).

VOs are used in one of Gaia’s calibration activities specially designed to investigate the level of serial CTI. The technique involves generating charge in the image area and then monitoring the trailing charge in the post scan pixels after the charge has been transferred. In this periodic activity, five different levels of charge are injected into each different science device and VOs are placed at the end of the image areas to monitor the
injected charge level and obtain post-scan pixels. This calibration activity was initially proposed to be run monthly or bi-monthly but due to the lower than predicted levels of CTI, it was changed to run every three to four months before being changed further to every 6 months in later years. Data from these calibration activities were used to produce the results of this chapter. At the time of analysis, 18 calibration activities had been run over a 6-year period, from the in-flight commissioning phase at the beginning of 2014 to the end of 2019. This period extends beyond the original mission lifetime range and these results can be compared with the predicted end-of-mission (EOM) results from the pre-flight studies (Crowley et al. 2016a, Crowley 2016c).

### 6.3 Data outline

Figure 6.2 outlines a section from one of the reconstructed images acquired from one of the serial CTI calibration activity runs. In the parallel or ALong-scan (AL) direction, the data consists of periodic blocks of 255 lines of charge injections (CIs) with a period of 455 TDI periods. This data is generated and transferred from one end of the CCD to the other in the parallel direction at the TDI transfer speed of 982.8 µs; it is then transferred to the readout circuit in the serial or ACross-scan (AC) direction in the serial register. The data is transferred across the entire serial register to maximise the amount of charge capture and trapping and subsequent CTI measurements. In the serial direction, two pre-scan pixels are read-out at the characteristic readout speed of the instrument. After this, the pixels are fast-flushed at 10 MHz until the image pixels reach the readout node; then the image and post-scan pixels are read out at the characteristic readout speed of the instrument.

While this data was originally designed to investigate just the serial CTI, the parallel CTI can also be investigated by analysing the CIs in the AL direction. In-flight parallel CTI is usually measured from the in-flight charge injections; these are carried out every ∼2 s (corresponding to a 2000 TDI period) on the AF devices and every ∼5 s (5000 TDI) for the BP and RP devices. Even though the RVS CCDs were built with a CI structure, regular CIs are not implemented on these devices as the signal would interfere too much with the finer measurements and long spectral windows and the leading edge of the long spectrum would act to fill the traps (Crowley et al. 2016a, Crowley 2016c).

The VOs in this analysis had a period of 455 TDIs which is much shorter than the
Fig. 6.2 A section from one of the charge calibration files. The charge injection blocks have a length of 255 TDI pixels with a period of 455 TDI pixels. No data is taken between the pre-scan pixels and the image pixels, so the charge packets are fast-flushed in the serial direction until they reach the readout node.

periods of the routine CIs. The period of the CIs is 2000 TDIs for the AF CCDs and 5000 TDIs for the photometers with the RVS CCDs having no CIs. The shorter period means that the parallel CTI values measured from the VOs will be lower than those that would have been measured from the regular CIs. This is because the lower period means that traps are less likely to have emptied between VOs.

There are still benefits to performing CTI analysis with this charge calibration data, despite the lower periods. It should still be possible to measure the change in CTI with time. As the charge calibration data has the same period and similar signal levels between all the CCDs, the CTI measurements between the different instruments can reliably be compared with each other. Due to the fact that this charge calibration data was also generated in the RVS devices, it means that the CTI in the RVS CCDs can also be studied in a level of detail that was not done before.

Given the format of the charge calibration data, both parallel and serial CTI measurements could be made from multiple points in the mission. Before any analysis could be performed, a number of processing steps were conducted to adjust the data into a suitable form, as detailed originally in a technical note illustrating a set of results from analysis of this data (Crowley 2016c).
6.4 Data processing and analysis

The charge calibration data was obtained in a raw form in ADU units as opposed to electrons. A dark image frame was also acquired from each CCD along with the five different CI level frames. This dark image frame was subtracted from each of the CI frames to remove the electronic background which would have included effects such as bias levels and glitches. After this, data processing proceeded differently depending on whether the serial or the parallel CTI was being investigated.

**Serial CTI:** To calculate the CTI in the serial direction, a single CI profile is extracted from each of the five CI signal levels for each CCD at each different timestep. The mean of all the CI profiles in the AC direction was taken. The resulting CI AC profile consisted of two prescan pixels, a number of image area pixels and a number of postscan pixels. The inverse gain is then applied to the data which converts from ADU units into number of electrons. Figure 6.3 depicts the resulting CI AC profiles for a single signal level for a CCD at different time steps.

**Parallel CTI:** To calculate CTI in the parallel direction, several CI vectors are extracted in the AL direction for each different AC coordinate that corresponds to a charge injection. The CI vectors were chosen to consist of 5 pixels before the CI, the 255 CI

![AC profiles](image)

**Fig. 6.3** AC profiles (co-added and background-subtracted as described in the text) of the highest level of injected charge during the 18 runs of charge calibration activity used in this study. The pre-scan, image area and post-scan pixels are all highlighted in the figure. A slow but measurable degradation in the CTI is visible. The AC profiles are made from the mean of the charge packets in Figure 6.2 in the AC direction.
pixels and 50 pixels trailing the CI. The mean of these 310-pixel length profiles was taken for each different AC coordinate, so a mean profile is produced for each different coordinate. The background level was taken as the signal level in the 50th pixel after the last CI pixel. Figure 6.4 outlines the CI AL profiles for a single signal level for a CCD at a single time step. Interestingly, a droop is present in most of the CIs where the signal level decreases with each pixel, as has been noted in the previous chapter and other studies (Crowley 2016c). The physical origin of this droop is unknown and is something that is ignored for now. The profiles for each AC coordinate could be used to investigate CTI in specific columns to check for any abnormalities, however, for the purposes of this study, the mean of all these CI profiles is taken so only one CI profile is produced per signal level. Like the serial CTI, the inverse gain is applied to the data to convert the units into numbers of electrons.

Fig. 6.4 AL profiles (co-added and background-subtracted) for each AC coordinate of the highest level of injected charge from a charge calibration activity run at the beginning of 2016. The AL profiles are found from each AC coordinate that contains a charge injection, as illustrated in Figure 6.2.

To calculate the CTI in the data and the CI profiles, the Extended Pixel Response (EPER) CTI measurement technique is used, as detailed in the previous chapter. While chapter 5 used simplified EPER measurements by examining the relationship between the deferred charge and the signal level to reduce the effects of noise, the comparatively larger amount of charge calibration data available in this analysis means it is possible to make by-the-book EPER CTI measurements using equation 5.2.
For the analysis of the charge calibration data, the signal level was taken as the charge in the last pixel of the CI image profile, a 10-pixel tail was used for the deferred charge and the number of transfers was taken to be 1980 for serial CTI and 4500 for parallel CTI (the number of pixels in each CCD in each direction). For parallel CTI in particular, the background level measured in the 50th pixel was subtracted from the charge levels in all the pixels of the tail to minimise the influence of background light on the measurements. At each timestep in the available data, five sets of CTI and signal value pairs are produced for each different scientific CCD.

Compared to EPER, where measurements are taken from the charge tail, First Pixel Response (FPR) probes charge captured from the beginning of a signal and is comparatively a better indicator of the number of traps present as the signal is lost from all the traps, regardless of the emission time constants. Unfortunately, FPR analysis could not be performed in either the serial or the parallel directions in this analysis, due to a number of limitations in the data. The data in the serial direction showed no noticeable or measurable signs of FPR that could be analysed as seen in Figure 6.3; this is likely due to the two-phase register design. While FPR is present in the parallel direction in some of the data files, there are a number of peculiar cases where the charge in the first pixel is higher than it should be, as indicated in Figure 6.4. The physical origin for this higher-than-expected charge is unknown but because it is not an outlier and is present in several data files, a reliably conducted FPR analysis would have required an excessive amount of data processing. Given the amount of time and effort needed for this analysis and the fact that the goals of this chapter are accomplished with EPER measurements, FPR analysis was not performed.

In general, EPER CTI results can vary depending on the transfer speed due to different trap species having different emission time constants. The parallel charge transfer takes place at Gaia’s TDI scanning speed of 982.8 µs, so parallel EPER measurements will be from traps emitting around this timescale. Charge transfer in the serial direction is slightly more complex; pixels are transferred across the serial register at a fast flush of 10 MHz. After this, they are read out at a slower speed in the kHz range; the exact value of which is different depending on the instrument (Mora et al. 2016, Cropper et al. 2018). This means that the effects of traps on both timescales will be seen. Considering the emission time constants of known trap species at these speeds and also considering
that the charge calibration is generated at the end of the CCD, meaning it is fast-flushed across the entire serial register, it is assumed that the MHz transfer and traps emitting along this timescale will dominate the serial CTI.

6.4.1 Single CCD results

Once the signal and CTI value pairs are obtained, they can be plotted against each other for each different CCD at different times. Figure 6.5 and Figure 6.6 illustrate the serial and parallel CTI results, respectively, for a CCD (AF5, Row 5) towards the centre of the focal plane, obtained from this calibration data. As is expected, the CTI is noted to increase in time as the CCDs undergo more radiation damage. It can be seen that the initial serial CTI is an order of magnitude higher than the initial parallel CTI. This is not surprising as the data is transferred at a high flush speed in the serial direction, which is on a comparable timescale with the A-centre trap defect. The A-centre is a trap defect formed from impurity Oxygen and has a relatively faster emission time constant compared to other trap defects. By comparison, the parallel transfer speed is slower and was specifically chosen to reduce the CTI impact from radiation-induced trap defects that were known at the time.

![CCD Row 5; AF5](image)

Fig. 6.5 The increase of the serial CTI with time for five different signal levels from the charge calibration data. This data was taken from the AF5 CCD in Row 5.

It is noted in Figure 6.6 that the parallel CTI shows a less consistent trend in its behaviour, fluctuating much more between different time-steps. This is likely due to
Fig. 6.6 The increase of parallel CTI with time for five different signal levels from the charge calibration data. This data was taken from the AF5 CCD in Row 5; compared to the serial CTI in the same CCD in Figure 6.5, there is a greater amount of noise. 

more noise being present when conducting the parallel CTI analysis. Some of this noise may be attributed to varying levels of background straylight which, while mitigating charge loss in signals, would add signal in the trailing edge of any signals or images (Brown 2010). This chapter only deals with the long-term effects and behaviour of the parallel CTI, so while this outlier effect is noted, it is not mitigated against, which means that some small order of uncertainty will be present in the measurements. This order of magnitude precision is not expected to affect the long-term CTI results. The relationship between CTI, signal and background level is explored through the analysis of on-ground datasets in Chapter 7.

It is seen in Figure 6.5 and Figure 6.6 that the signal levels are not exactly identical and deviate slightly around a mean value. This effect is particularly prevalent in the lowest CI level. In order to reliably compare the results from each different CCD against each other, a power law fit was made at each time-step of the CTI against the signal level, using equation 6.1.

\[
CTI = \alpha \times \text{Signal}^n
\] (6.1)

Using fitted values for the parameters \( \alpha \) and \( n \), equation 6.1 was used to extrapolate a CTI value for the same ‘virtual’ signal for all the CCDs. This produces CTI values for...
the same signal across all the CCDs so they can be compared against each other. The serial and parallel CTI results obtained from this method are detailed in the subsequent sections. The power law fit was chosen due to a variation of such a relationship having been used in Gaia’s pre-flight simulation studies (Short et al. 2013) as well as the fact that it has been verified in other experimental studies (Hall et al. 2015). A virtual signal of 10,000 electrons was used in these calculations and all subsequent results in this chapter. This value was used in previous studies of Gaia CTI data and represents a signal level that is comparable to the charge injections and is well beyond the SBC capacity. The signal levels in the charge calibration data were predominantly much larger than the maximum theoretical SBC FWC, so effects and behaviour of the SBC are ignored in the analysis performed in this chapter.

In spite of the use of the power-law fit in other studies, however, it was not always an exact fit with this data, especially with the noisier parallel CTI data. It is assumed that most of the results obtained from the power law measurements are reasonably accurate and consistent when looking at the long-term trends and behaviour.

If equation 6.1 is combined with the EPER CTI equation 5.2 and the terms are re-arranged, a new equation 6.2 is obtained, as detailed below

\[ S_D = \alpha \times N_P \times \text{Signal}^{(1+n)} \]  

Equation 6.2 is now in a similar form to equation 5.3 and where deferred charge is on one side of the equation and is equal to constant terms multiplied by the signal, raised to a power. Similar to how equation 5.3 was considered equivalent to equation 4.1, equation 6.2 can also be considered equivalent to equation 4.1 where \( S_D \), the deferred charge, is analogous to \( V_c \), the volume confined by the signal. This means that the \( \beta \) value from equation 4.1 is equal to the power \((1+n)\) from equation 6.2. The average fitted value of \( n \) that was obtained from fitting equation 6.1 onto most of the charge calibration data was \( \sim -0.48 \). Using the analysis described, this returns a \( \beta \) value of 0.52 for the Gaia CCDs. This \( \beta \) value is consistent with the results from the analysis in Chapter 5 and is utilised in the investigations in Chapter 8.

A limitation in this work that was not accounted for, was the dependence on CTI with respect to temperature and background straylight. It is known that both of these properties have a small but finite effect on the measured CTI. Differing amounts of
straylight can mitigate against charge loss whilst at the same time causing increased background noise causing counter-intuitive effects on the CTI (Brown 2010). While Gaia’s temperature is relatively stable at 163.15 K, there is a known small gradient across the focal plane which can cause small differences in the measured CTI between different devices (Crowley et al. 2016a,b). These effects are not expected to produce any drastic CTI differences, especially when considering the evolution over large time-scales, so are not considered here; straylight analysis is detailed in Chapter 7.

6.5 Serial CTI (AC Direction)

6.5.1 2014 and 2019 data

Using the data analysis steps outlined in the previous section, the diagrams in Figure 6.7 were generated, which highlight the serial CTI of all the CCDs at two different points in the mission. Figure 6.7(a) illustrates the CTI in April 2014, just a few months after launch, while Figure 6.7(b) illustrates the CTI in December 2019, over five years later. The mean CTI for each instrument was also calculated at these two times and these values are given in Table 6.1. The calibration data from January 2014 was not used as the cool-down of the payload was still not complete. Figure 6.7(a) is similar to the plot generated in the previous set of results in 2016, verifying the reliability of these results. It is assumed that the oxygen defect, called the A-centre, is likely to be responsible for the bulk of the serial CTI as it has a comparable release time with the 10-MHz flush that dominates the serial transfer. A previous pre-flight test revealed a trap species that emitted faster than the A-centre so there is a chance for the AC CTI to be caused from this trap species as well (Crowley et al. 2016a, Hopkinson et al. 2005).

Table 6.1 Mean serial CTI (at 10,000 electrons) for each instrument as measured in April 2014 and December 2019.

<table>
<thead>
<tr>
<th>CCD Instruments</th>
<th>2014 mean CTI ($\times 10^{-5}$)</th>
<th>2019 mean CTI ($\times 10^{-5}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF</td>
<td>3.5 ± 0.3</td>
<td>3.8 ± 0.3</td>
</tr>
<tr>
<td>BP</td>
<td>3.6 ± 0.2</td>
<td>3.8 ± 0.2</td>
</tr>
<tr>
<td>RP</td>
<td>1.5 ± 0.1</td>
<td>1.9 ± 0.1</td>
</tr>
<tr>
<td>RVS</td>
<td>1.5 ± 0.1</td>
<td>1.9 ± 0.1</td>
</tr>
</tbody>
</table>

The 2014 serial CTI results in Figure 6.7(a) and Table 6.1 should be reflective of
Fig. 6.7 The distribution of the derived serial CTI values across the focal plane for a signal of 10,000 electrons as measured in (a) April 2014 and (b) December 2019.

The initial CTI state of the CCDs as the accumulated radiation damage within the first few months is known to be minimal. The results show that the thicker RP devices, found in both the RVS and the RP, all measure a lower serial CTI as compared to the other devices. Thicker devices are known to have different properties to thinner devices, such as being more sensitive to cosmic rays and having larger amounts of dark current.
(Holland et al. 2003). However, it is currently unknown why these devices would be manufactured measuring a lower serial CTI compared to thinner devices with the same architecture. If the serial CTI is indeed primarily caused by A-center traps, then this could be due to a smaller amount of oxygen and A-center defects being present in the buried channel region. This could have been the result of impurity oxygen having a larger amount of silicon to diffuse through during manufacture. It would be useful to perform trap-pumping on unirradiated thick and thin devices to understand the trap landscape and narrow down the reasons behind this behaviour. Trap-pumping is an analysis technique that makes it possible to observe individual trap species and their properties with a high level of accuracy and quantify their densities. It involves the clocking of a flat-field signal between phases which leads to the formation of dipole maps that can be studied in more detail (Hall et al. 2014, Wood et al. 2014, Murray et al. 2013).

It can be seen that the pattern of serial CTI distribution across the focal plane is the same in 2014 and 2019. This indicates that the initial CTI state continues to dominate the serial CTI and that the amount of radiation damage over six years has not been significant enough to change this distribution pattern. The 2019 CTI values in Table 6.1 are within the same order of magnitude as the 2014 CTI values; this demonstrates a very low rate of increase. The AF and BP CCDs measure a smaller percentage increase in their serial CTI (∼6% to 9%) as compared to the red variant devices (∼27%). With Gaia having been in orbit for just over its original mission lifetime, no major deviations are seen from the previous set of CTI results, as measured in 2016.

6.5.2 Rate of Increase

Using the serial CTI values for each CCD at the time of each calibration activity, a linear relationship was fitted between serial CTI and time, using equation 6.3.

\[ CTI = m \times Time + C \] (6.3)

The fitted value for the gradient \( m \) from equation 6.3 was taken as the rate of increase of CTI with time and was computed for each CCD; these values are illustrated for each CCD in Figure 6.8. If outliers are ignored, the column-wise CTI distribution would
seem loosely similar to the NIEL-dose prediction from Fig. 6.1, however, the pattern is not very clearly defined so a correlation cannot be reasonably established.

![Diagram](image)

**Fig. 6.8** The extrapolated rate of increase of serial CTI (at 10,000 electrons) for each CCD during the six-year period of the charge calibration data.

Combining the data from the CCDs for each instrument, the values in Table 6.2 are produced which gives the mean rate of increase for each instrument, in units of both Gaia revolutions and in years. Figure 6.9 shows the mean CTI for each instrument and how it increases with time; the values were calculated for each calibration activity run. Three major sets of solar flares are also marked out; the events in 2014 and 2015 had notable effects in the previous set of data analysis of in-flight parallel CTI (Crowley et al. 2016b). Interestingly, these events do not seem to have a significant impact on the serial CTI. In contrast, the solar flare events in 2017, which were larger and more powerful, make a slightly more noticeable impact on this set of charge calibration data. This could be due to the relatively high level of CTI from the beginning of the mission which means the relative contribution from a solar event is much less evident on serial CTI. There is a loosely linear increase of CTI in time, justifying the use of a linear extrapolation with equation 6.3 for the results of Figure 6.8 and Table 6.2. The fluctuations and uncertainties seen in the data are likely due to photon noise from straylight and noise from bias and background subtraction during data processing.
Table 6.2 Mean increase in serial CTI per time for each instrument on the focal plane for a signal of 10,000 electrons.

<table>
<thead>
<tr>
<th>CCD instruments</th>
<th>CTI Increase Revs$^{-1} \times 10^{-10}$</th>
<th>CTI Increase Year$^{-1} \times 10^{-7}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF</td>
<td>5.5 ± 0.9</td>
<td>8.0 ± 1.0</td>
</tr>
<tr>
<td>BP</td>
<td>4.0 ± 1.0</td>
<td>6.0 ± 1.0</td>
</tr>
<tr>
<td>RP</td>
<td>6.0 ± 0.3</td>
<td>8.8 ± 0.4</td>
</tr>
<tr>
<td>RVS</td>
<td>5.7 ± 0.8</td>
<td>8.0 ± 1.0</td>
</tr>
</tbody>
</table>

Fig. 6.9 Evolution of the mean serial CTI for each instrument, calculated from the CTI measured from all the devices at each different time. There is a steady, linear increase in time with fluctuations likely due to noise. Three main sets of solar flare events are all marked out. The $x$ axis spans a little under six years.

From the results of Figure 6.8, Figure 6.9, and Table 6.2, it can be seen that the RP devices in the RP and RVS instruments measure comparatively higher rates of CTI increase as compared to the other devices. It is known from Figure 6.1 that the Blue and RPs receive an equivalent amount of fluence, likely due to similar levels of shielding. In the future, more experimental tests will need to be conducted to more precisely determine the physical reasons behind the calculated higher increase. Current hypotheses include the initial CTI state or the geometry of the devices affecting the rate of radiation damage as well as interactions between the shielding and the radiation altering the energy spectrum of incoming particles. An analysis was performed to try and get a better understanding of this behaviour.
Using the value for the “initial” CTI, obtained from the value of $C$ from fitting equation 6.3, a scatter plot can be made of the rate of CTI increase against the initial CTI for all the CCDs. This scatter plot is detailed in Figure 6.10 and is used to check for any correlations and unusual behaviour. The fitted $C$ value was used to reduce the uncertainty as noise is present in the real CTI measurements. The AF devices were split between those from AF1 and the other strips because the AF1 CCDs had a different readout rate; the data was split to try and separate out all the different factors that could affect the CTI.

From Figure 6.10, it would appear as if the device variant does not have an impact on the rate of CTI increase. Despite the lower initial CTI value of the red devices, it can be seen that their rate of increase is comparable with those of the AF devices. However, despite having relatively similar levels of shielding with the Red devices, the BP devices show relatively lower rates of serial CTI increase. This would suggest that the larger increase in CTI in the red devices is probably due to the nature of them being...
different, thicker devices as opposed to being about the shielding. This might be due to the thicker devices being able to stop particles over a larger range of energies than the thinner devices, making them far more vulnerable to radiation in space. However, the number of traps would be a function of the buried channel volume and should be independent of the depletion depth so the extra damage theoretically should not affect the number of traps formed in the buried channel. It could be possible that the active volume of the buried channel is slightly higher for the thick, high-resistivity device. Regardless of the physical reasons behind this larger CTI increase, it would seem that this dominates over whatever shielding is available for the devices.

6.5.3 NIEL-Scaled Rate of Increase

Understanding the evolution of CTI for a single CCD is useful for making predictions on its performance and designing models to correct the data. However, it is known that the devices do not all receive the same dose, as outlined by the NIEL-dose prediction in Figure 6.1. This is evident in Figure 6.8 and Table 6.2 where there is a large variation in the CTI increase of the various AF devices due to the NIEL dose. By scaling the rate of increase results by the NIEL values from Figure 6.1, it becomes possible to remove the variation in dose and shielding effects and examine the CTI increase between each CCD variant against each other more reliably. Figures 6.11 and 6.12 reproduce Figures 6.8 and 6.10 but with the rate of increase values of each CCD scaled by their corresponding NIEL dose value from Figure 6.1. Table 6.3 also has recalculated rate of CTI increase values for each different instrument after the CCD values are scaled by the NIEL dose.

Table 6.3 NIEL-scaled mean increase of serial CTI per time for each instrument on the focal plane for a signal of 10,000 electrons.

<table>
<thead>
<tr>
<th>CCD Instruments</th>
<th>CTI Increase (NIEL scaled) Revs$^{-1}$ (×10$^{-10}$)</th>
<th>CTI Increase (NIEL scaled) Year$^{-1}$ (×10$^{-7}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF</td>
<td>1.8 ± 0.3</td>
<td>2.6 ± 0.4</td>
</tr>
<tr>
<td>BP</td>
<td>2.6 ± 0.5</td>
<td>3.8 ± 0.8</td>
</tr>
<tr>
<td>RP</td>
<td>3.8 ± 0.3</td>
<td>5.6 ± 0.4</td>
</tr>
<tr>
<td>RVS</td>
<td>3.1 ± 0.5</td>
<td>4.5 ± 0.7</td>
</tr>
</tbody>
</table>

In Figure 6.11, the AF devices now all highlight rates of CTI increase that are more comparable to each other as the shielding pattern from Figure 6.1 is removed. This would indicate that all the AF CCDs experience radiation induced CTI increase on
Fig. 6.11 The extrapolated rate of increase of serial CTI (at 10,000 electrons) for each CCD during the six-year period of the charge calibration data with each CCD scaled by its corresponding NIEL dose value from Fig. 6.1.

Fig. 6.12 The extrapolated rate of serial CTI increase ($m$ from equation 6.3), scaled by the NIEL-dose against the extrapolated initial CTI value ($C$ from equation 6.3) for all the scientific CCDs.
equivalent levels to each other. An interesting observation from Figure 6.11, Figure 6.12 and Table 6.3 is that even after accounting for the NIEL dose, the RP devices still measure larger rates of CTI increase which are not measured by any of the other device variants. This gives more credence to the idea that it is a unique property of the thick RP devices that is causing this larger increase in CTI. It remains to be seen whether this feature is due to the lower initial CTI, an additional unknown effect of shielding not accounted for in the NIEL dose calculation, the manufacture of the devices, or due to device geometry.

It is noted from Figures 6.11 and 6.12 that some of the BP devices seem to have rates of CTI increase that are more comparable to the RP devices than with the AF and BP devices. This would suggest that despite the reduced impact from the 10 MeV equivalent NIEL-dose, the shielding from the optics and photometers could somehow be affecting the radiation damage in a counterintuitively more destructive manner. This could be due to radiation interfering with the optics and photometers in some way, either causing secondary emissions or slowing down higher energy particles that may not have caused damage otherwise. In previous on-ground studies, it has been reported that aluminium shields in front of CCDs have caused higher energy particles to lose some of their kinetic energy so a similar phenomenon could be occurring here (Hopkinson et al. 2005). Given only some BP devices measure this relatively higher increase though, this effect appears to be minimal, at least for the serial CTI.

Returning briefly to the overall increase of CTI in the context of the Gaia mission, it is noted from Tables 6.2 and 6.3 that the rate of increase of CTI per year is on the order of magnitude of $10^{-7}$. This is at least two orders of magnitude smaller than the CTI values at the beginning of the mission, as noted in Table 6.1. This illustrates that the degradation of the serial CTI from the current status is very low.

**6.6 Parallel CTI (AL Direction)**

**6.6.1 2014 and 2019 data**

In a similar procedure to the serial CTI, the parallel CTI distribution of the CCDs across the focal plane in April 2014 was also reproduced, as given in Figure 6.13. The results in Figure 6.13 are similar to previous CTI results that were taken for the CCDs before
launch, both validating the data analysis procedure and confirming that the parallel CTI after launch is almost identical to the CTI before launch and extremely low (Crowley 2016c).

Fig. 6.13 The distribution of the parallel CTI values across the focal plane as measured in April 2014 for a signal of 10,000 electrons.

Comparing the parallel CTI results to the year of manufacture of the devices from Chapter 4’s Figure 4.2 reveals the same observation from Chapter 5 where all the devices manufactured in 2009 measure a higher initial CTI as compared to the devices manufactured in earlier years. This effect is seen and confirmed with several other RP variant devices as well. As discussed in Chapter 5, it is currently unknown why this may be. It could be due to a change in the manufacturing process or due to the use of a different silicon feedstock. When comparing Figure 6.13 with Figure 4.2, it appears as if this peculiarity is not dependent on the device variant as the RP devices manufactured in earlier years have comparable CTI values with the other device variants.

Figure 6.14 shows the distribution of the parallel CTI across the focal plane from the data taken in December 2019. This is several months past the original mission end date which means the results can be compared with the pre-flight tests to quantify the disparity between the two. As was the case for the serial CTI, the distribution pattern in 2019 is more reflective of the initial CTI state from 2014 than the predicted NIEL
dose pattern. This suggests that the radiation damage has not been significant enough to drastically alter the CTI distribution across the focal plane. It also indicates that the long-term radiation damage contribution from the solar protons has been minimal as the NIEL pattern is not evident in Figure 6.14. This lack of a clear NIEL pattern could also be due to the scale of the CTI values, which is limited by the red devices; previous studies have illustrated the pattern when studying just the AF devices (Crowley et al. 2016a).

Table 6.4 gives the mean parallel CTI measurements for each instrument as measured in April 2014 and December 2019. To more reliably compare the devices against each other, the RP devices are split for their year of manufacture instead of by instrument. Comparing the 2014 CTI values in Table 6.4 to those in Table 6.1, it can be seen that the parallel CTI is up to two orders of magnitude lower than the initial serial CTI. In addition to this, the initial CTI measured by the 2009 devices is calculated to be higher by an order of magnitude as compared to the other devices.

The 2019 CTI values in Table 6.4 for each instrument and CCD variant are within the same order of magnitude with respect to each other. This verifies that there is no apparent dependence between the initial parallel CTI and the rate of increase of CTI.

Fig. 6.14 The distribution of parallel CTI values across the focal plane as measured in December 2019 for a signal of 10,000 electrons.
Table 6.4 Mean parallel CTI (at 10,000 electrons) for each instrument as measured in April 2014 and December 2019.

<table>
<thead>
<tr>
<th>CCD instruments</th>
<th>2014 mean CTI ($\times 10^{-6}$)</th>
<th>2019 mean CTI ($\times 10^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF</td>
<td>0.17 ± 0.09</td>
<td>1.6 ± 0.2</td>
</tr>
<tr>
<td>BP</td>
<td>0.18 ± 0.09</td>
<td>1.3 ± 0.3</td>
</tr>
<tr>
<td>RP (pre-2009)</td>
<td>0.4 ± 0.2</td>
<td>1.8 ± 0.2</td>
</tr>
<tr>
<td>RP (2009)</td>
<td>1.7 ± 0.5</td>
<td>3.6 ± 0.6</td>
</tr>
</tbody>
</table>

6.6.2 Rate of Increase

As was conducted for the serial CTI, a linear relationship was extrapolated between the CTI for each CCD and time, using equation 6.3. Figure 6.15 shows the distribution of the rate of increase values, derived from the fitted values of $m$, across the focal plane. The NIEL-dose pattern across the AF devices from Figure 6.1 is not present in Figure 6.15; in previous results, the NIEL pattern has been visible across the focal plane for parallel CTI but only after the devices are investigated straight after the occurrence of a solar event (Crowley et al. 2016a). Parallel CTI degradation is most likely predominantly caused by other sources, such as higher energy GCRs; previous analysis of in-flight data have calculated that GCRs are responsible for around 75% of the parallel CTI degradation (Crowley et al. 2016b).

Table 6.5 outlines the mean increase of CTI per instrument, also split by the year of manufacture for the RP devices to analyse effects of initial CTI. From Table 6.5, it can be seen that the CCDs with the higher initial CTI measure relatively the same rate of increase as the other devices. This demonstrates that the initial CTI does not affect the increase of CTI from radiation-induced traps; an expected result as the defects responsible for parallel CTI from manufacturing and radiation damage are known to be different. The rate of parallel CTI increase for all the devices is the same order of magnitude as it was for the serial CTI increase. This is likely an indication of the fact that serial and parallel CTI are caused by different trap species and that they form independently of each other.

Figure 6.16 shows the mean CTI increase for the AF and BP instruments as well as the RP devices, split by their year of manufacture, over 6 years. Compared to results from previous studies (Crowley et al. 2016b,a) the impact of the 2014 and 2015 solar flare events on the parallel CTI is less substantial. This could be due to the lower
Fig. 6.15 The extrapolated rate of parallel CTI increase for each CCD as derived from the 6 years of charge calibration data, for a signal of 10,000 electrons.

Injection period and different signal values used in this data, as well as a comparatively higher level of noise present in this dataset. The 2017 solar flare events cause a much more obvious impact on the CTI, with big step increases in the CTI for each instrument. The 2009 RP devices measure larger uncertainties in the CTI, likely due to the larger variance in the pre-flight trap defect concentrations and corresponding initial CTI values across fewer devices (as shown in Figure 6.13), which seem to be more dominant over the radiation induced CTI. Similar to the serial CTI, a loosely linear increase of CTI in time is observed.

To see if there is any relation between the rate of CTI increase and the initial level of CTI, the fitted values of $m$ and $C$ from equation 6.3 extrapolated from each CCD, is plotted against the initial CTI in Figure 6.17. The negative values of the initial CTI are due to the fitted $C$ values and not physically representative of the actual CTI. Instead of splitting the RP data by instruments, as was the case in the serial CTI results, the RP devices are split by their year of manufacture, which has been noted to be the cause of the higher initial CTI compared to the other devices. Interestingly, as noted before, it appears as if the rate of CTI increase has no dependence on the initial CTI, with no discernible trends or behaviours in the Figure. This can be seen from the 2009 devices.
Table 6.5 Mean rate of increase of parallel CTI increase for each instrument for a signal of 10,000 electrons. The RP variants are additionally split by their year of manufacture.

<table>
<thead>
<tr>
<th>CCD Instruments</th>
<th>CTI Increase Revs$^{-1}$ $(\times 10^{-10})$</th>
<th>CTI Increase Year$^{-1}$ $(\times 10^{-7})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF</td>
<td>1.6 ± 0.2</td>
<td>2.3 ± 0.3</td>
</tr>
<tr>
<td>BP</td>
<td>1.4 ± 0.3</td>
<td>2.0 ± 0.5</td>
</tr>
<tr>
<td>RP</td>
<td>1.7 ± 0.4</td>
<td>2.4 ± 0.5</td>
</tr>
<tr>
<td>RVS</td>
<td>1.8 ± 0.1</td>
<td>2.6 ± 0.2</td>
</tr>
<tr>
<td>RP (Pre-2009)</td>
<td>1.7 ± 0.2</td>
<td>2.5 ± 0.4</td>
</tr>
<tr>
<td>RP (2009)</td>
<td>1.8 ± 0.3</td>
<td>2.6 ± 0.4</td>
</tr>
</tbody>
</table>

Fig. 6.16 Evolution of the mean parallel CTI (at 10,000 electrons) for each instrument, calculated from the CTI measured from all the devices at each different time. Instead of instrument, the thicker red devices are split by their year of manufacture. There is a steady, linear increase in time with fluctuations likely due to noise. Three main sets of solar flare events are all marked out. The x axis spans a little under six years. The data from 04 November 2014 was omitted as it was defective for a number of devices.

having comparable rates of increase to the other devices. On average, from the results of Figure 6.15 and 6.17, it seems as if the RP devices measure slightly higher rates of increase compared to the other devices, possibly due to the reasons detailed in the previous section.
Fig. 6.17 The extrapolated rate of parallel CTI ($m$ from equation 6.3) increase against the extrapolated initial CTI value ($C$ from equation 6.3) for all the scientific CCDs. The unit of time used was OBMT satellite revolutions.

6.6.3 NIEL-Scaled Rate of Increase

To compare the CCD variants more reliably, the rate of increase of CTI for each CCD was scaled by the corresponding NIEL dose values from Figure 6.1. This produces Figures 6.18 and 6.19, derived from Figures 6.15 and 6.17. Table 6.6 details the mean rate of parallel CTI for each instrument after the individual CCD rates have been scaled by their corresponding NIEL value. Given that there was found to be no apparent dependence on the initial CTI in Table 6.5, the RP devices are not split by manufacture year in Table 6.6. From Figures 6.18, 6.19 and Table 6.6, it can be seen that the BP and RP devices both measure higher CTI increases as compared to the AF devices, roughly by a factor of 2. Interestingly, both these sets of devices were predicted to have a lower 10-MeV equivalent dose, as was seen in Figure 6.1.

The BP devices are identical to the AF devices aside from having a different thickness of hafnium oxide coating to increase the quantum efficiency of the BP devices to bluer wavelengths and having photometers placed in front of the devices. While no studies have looked into the effects of AR coatings on CTI, these are not believed to have a significant contribution. One current hypothesis is that the optics and photometers, alongside the higher energy GCR particles could be causing this increased damage
Fig. 6.18 The extrapolated rate of parallel CTI increase for each CCD as derived from the 6 years of charge calibration data, for a signal of 10,000 electrons, scaled by each CCD’s corresponding NIEL-dose value from Figure 6.1.

Fig. 6.19 The extrapolated rate of parallel CTI \((m\) from equation 6.3\) increase against the extrapolated initial CTI value \((C\) from equation 6.3\) for all the scientific CCDs, scaled by their NIEL dose values.

in the BP devices, while also explaining the behaviour of the RP devices. Hypothetically, particle energies will reduce when passing through the optical setups allowing for more displacement damage per particle in the devices.
Table 6.6 Mean rate of increase of parallel CTI increase (at 10,000 electrons) for each instrument, scaled by the NIEL-dose values from Figure 6.1.

<table>
<thead>
<tr>
<th>CCD Instruments</th>
<th>CTI Increase (NIEL scaled) Revs$^{-1}$ ($\times 10^{-10}$)</th>
<th>CTI Increase (NIEL scaled) Year$^{-1}$ ($\times 10^{-7}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF</td>
<td>0.51 ± 0.07</td>
<td>0.7 ± 0.1</td>
</tr>
<tr>
<td>BP</td>
<td>0.9 ± 0.2</td>
<td>1.3 ± 0.2</td>
</tr>
<tr>
<td>RP</td>
<td>1.0 ± 0.1</td>
<td>1.5 ± 0.2</td>
</tr>
<tr>
<td>RVS</td>
<td>1.0 ± 0.2</td>
<td>1.5 ± 0.2</td>
</tr>
</tbody>
</table>

6.7 Comparisons with on-ground data and other missions

In the previous analysis of in-flight data, as detailed in Chapter 4, comparisons were made with on-ground data taken from an irradiated flight-model CCD using the Gaia test bench at the ESA/ESTEC site in The Netherlands (Crowley et al. 2016b). By reproducing and extrapolating the results from the previous analysis (with permissions from the original author) and comparing them with the results of the in-flight calibration data from December 2019, it becomes possible to make another comparison between the on-ground and in-flight results. This is visualized in Figure 6.20, with fractional charge loss measurements calculated as the total charge in the trailing pixels divided by the signal level (taken as the value of the final CI pixel). This fractional charge loss measurement is loosely similar to the deferred charge against signal level measurements from Chapter 5.

For a signal of up to 10,000 electrons, the fractional charge loss of the in-flight results was smaller than the extrapolated on-ground charge loss by a factor of $\sim 20$ for the CCDs manufactured before 2009 and a factor of $\sim 11$ for the CCDs manufactured in 2009. For larger signals around 40,000 electrons, the in-flight fractional charge loss was smaller than the corresponding on-ground charge loss by a factor of $\sim 13$ for the pre-2009 manufactured devices and a factor of $\sim 9$ for the 2009 devices. While it would appear as if the CCDs are functioning better than the factor of 7–8 difference measured in 2016 (Crowley et al. 2016b), a number of elements are making this difference higher than it actually is. These reasons include the lower CI period as described in Section 6.2 (as compared to the previous in-flight and on-ground periods) as well as the higher irradiation on the on-ground devices. After accounting for all the determinants, it is likely that the accumulated radiation damage has not deviated significantly from the
Comparing the results of CTI increase in Gaia with those from other space missions allows for a greater understanding of radiation environments in space and allows for a verification of the results between this research and other studies. Other space missions that have utilised charge-coupled devices include the Hubble Space Telescope (HST), the Chandra X-Ray Observatory, and XMM-Newton. Compared to Gaia which orbits at Lagrange Point 2 (L2), HST is in Low-Earth Orbit (LEO) while Chandra and XMM-Newton are in elliptical orbits around the Earth. Given that the radiation environments of the spacecraft are all different, there will be obvious disparities between the CTI results for the different space missions.

Despite the difference in environment, the CTI measurements from Hubble are noted to have similarities with the Gaia CTI measurements described in this chapter. The CTI results from the CCDs on Hubble’s Advanced Camera for Surveys (ACS) and Wide Field Camera 3 (WFC3) have also show a power-law dependence between CTI and signal as well as a linear dependence between CTI and time. Compared to Gaia’s measured CTI increase of $10^{-7} \text{ year}^{-1}$ for a signal of 10,000 electrons, the CTI increase measured on ACS/WFC3 for an equivalent signal is around $10^{-6} \text{ year}^{-1}$ (Ryon and Groggin 2018). The CCDs on-board Chandra also measure an increase of CTI of $10^{-6} \text{ year}^{-1}$.
while the pnCCDs on XMM-Newton measure a larger increase of $10^{-5}\ \text{year}^{-1}$ (Grant et al. 2005, Strüder et al. 2003). A reason Lagrange Point 2, the location of Gaia, was chosen was because it has a more stable radiation environment as compared to elliptical Earth orbits, which is reflected by these measurements of the increase of CTI with year.

Understanding the radiation environment at L2, by proxy of investigating the damage experienced by Gaia’s CCDs, is crucial as a number of space missions are set to dock at that location such as ESA’s Euclid, PLAnetary Transits and Oscillations of stars (PLATO) and Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) missions. The rate of increase of both parallel and serial CTI seems to be on par with the previous measurements made with the in-flight data, which in turn has been lower than what was was predicted from the pre-flight on-ground tests. The solar activity has been unusually less active than was predicted so it cannot be said for certain whether the rate of CTI increase currently observed in Gaia is representative of the environment at L2 or is an outlier compared to the time of launch and mission durations for the other space missions. The factors responsible for the CTI results, including the radiation dose, will be discussed in the remaining chapters of this thesis.

6.8 Conclusions

This chapter has built on the work of the in-flight CTI analysis presented in Crowley et al. (2016a) and Crowley et al. (2016b). The previous studies examined the in-flight CTI in the first 30 months of the mission with the CIs. The work in this chapter has extended that CTI analysis to 72 months, using an alternate set of in-flight charge calibration data. Over this time period, the CTI evolution has been modest and has not varied substantially. Furthermore, the results have led to a more detailed characterisation of the CTI of the different devices and instruments on the focal plane. More links have been made between the initial CTI and the year of manufacture and differences have been noted in the CTI evolution of different devices.

This chapter has presented an overview of the CTI measurements of the science data measuring CCDs on-board Gaia over a six-year period. Many interesting results and insights have been revealed from these results with respect to the correlations between CCDs and radiation damage. It is noted that the baseline for the periodic charge calibrations, as of the beginning of 2021, has been reduced to a cadence of approxi-
It was observed that the pattern of the rate of increase of parallel and serial CTI has little similarity to the predicted 10 MeV equivalent NIEL dose pattern, which used a solar proton spectrum as an input. From other studies, it has been calculated that higher energy GCRs have been responsible for the bulk of the radiation damage (Crowley et al. 2016a). It is theorised that the energy of the incoming particles could have an effect on the production of various trap defects. Alternatively, the cryogenic space environment could be causing different effects in the formation of trap species as compared with room temperature irradiations from the on-ground tests; this effect could be more pronounced in the parallel direction than the serial (Crowley et al. 2016b). To test these hypotheses, irradiations of different energies, and at different temperatures, should be performed on the same type of CCD, after which trap-pumping should be conducted to understand the trap-landscape and how it is affected by the different factors.

The rate of CTI increase is measured to be the same order of magnitude in the parallel and serial directions, which is of the order of around $10^{-7}$ a year. This would suggest that the trap species responsible for parallel and serial CTI are unique and not competing against each other. It is currently unknown why different devices at the beginning of the mission were measured to have different amounts of CTI, be it the lower serial CTI for all the RP devices or the higher initial parallel CTI for the RP devices manufactured in 2009. It is recommended to perform trap pumping between different sets of un-irradiated devices, either thick and thin devices or the same devices manufactured at different times, to understand the trap-landscape differences between the device variants. This would provide a starting point into the nature of the trap defect map of CCDs of different architectures. It would also be useful to perform trap pumping on these same devices after irradiation as well, as the RP devices have been measured to have larger rates of increase than the other devices. This should provide more quantitative details on how different device variants are altered by radiation.

It has also been measured that the BP and RP devices measure relatively larger rates of increase (more evident in the parallel direction), than the AF devices. This is in contrast to the predicted 10-MeV equivalent dose across the devices. The current...
hypothesis for this is that the photometers and optics setup in front of the BP and RP devices could be interfering with the incoming radiation. One hypothesis is that higher-energy particles are losing energy to the optics and hitting the detectors at a lower energy and hence causing more damage. This would line up with the conclusion that higher energy GCRs have been causing more damage, but specifically designed simulations (such as with Geant4) or laboratory tests would need to be conducted to verify this.

Many different avenues for investigation are opened up, as detailed above. In the context of the Gaia mission itself, the devices are performing well at the time of this research and the measured CTI levels of the Gaia CCDs are well-below the pre-flight expectations after six years of orbit. The exemplary performance has led to mission extensions being granted which will increase the operation time and data collected for researchers. Following this additional examination of the in-flight CTI levels, the following chapters will examine the factors influencing the measured CTI values and draw on some of the information presented here. While this chapter has presented the analysis of serial and parallel CTI, the remainder of this thesis will only investigate parallel CTI.
CHAPTER 7

Straylight effects

7.1 Introduction

As discussed in the previous chapters, background straylight is a factor that can impact the CTI measured by the CCDs. Interestingly, illuminating a CCD with a uniform source of photons to generate a level of background light is a commonly applied charge loss mitigation technique. The signal from this background light can fill trap defects; because the interaction time between the signal from the background light and the traps is long, a low level of background becomes sufficient to decrease the CTI of the CCDs. This is a technique that is applied on the CCDs of the Hubble Space Telescope’s Wide Field Camera 3 with the use of broad filters, long exposure times and a post-flash with an on-board LED (Baggett et al. 2015). The use of an artificial light source was considered as one of Gaia’s CTI mitigation countermeasures, however the idea was discarded due to the significant noise increase and the marginal mitigating effect measured at the time (Prod’homme 2011).

During the in-flight commissioning phase after Gaia’s launch, unexpected and significant levels of straylight were measured on the focal plane. An investigation was undertaken to identify the sources of straylight which was found to be derived from two components. One was a non-solar component from the integrated light of the whole of the Galaxy from off-axis astrophysical sources, varying over the course of a 6-hour satellite revolution. The other component was solar straylight, produced from a combination of three different effects; fibres at the edges of the sun shield diffracting light, the sun-shield design allowing diffracted light to get through the thermal tent telescope apertures and rogue paths transporting the scattered light onto the focal plane (Mora et al. 2016, Crowley et al. 2016b). The straylight level has been measured to have
a median level of $5.5 \, \text{e}^{-}\text{pixel}^{-1}\text{s}^{-1}$ with the distribution measured to be less than $20 \, \text{e}^{-}\text{pixel}^{-1}\text{s}^{-1}$, 90% of the time (De Bruijne et al. 2014). While this straylight would no doubt increase the photon noise of the measurements, it is likely that some level of CTI mitigation would be taking place. This chapter discusses the effects of straylight on CTI in the context of Gaia with results from previous studies and analysis of new data.

### 7.2 Previous results

The effects of background light were investigated during the pre-flight radiation campaigns where the primary goal was to measure the stellar image location pre-flight biases as a function of background level. It was found that a very low level of background was able to provide a reasonable degree of CTI mitigation but increasing the background level further provided diminishing returns. The CTI mitigation was larger when the background was increased from 0 to $5 \, \text{e}^{-}\text{pixel}^{-1}\text{s}^{-1}$ as opposed to 5 to $10 \, \text{e}^{-}\text{pixel}^{-1}\text{s}^{-1}$. These on-ground measurements were performed using a CCD irradiated at room-temperature to a fluence of $4 \times 10^9 \text{p}^+ \text{cm}^{-2}$ at the 10 MeV equivalent NIEL dose (Seabroke et al. 2008, Brown 2010).

After Gaia was launched and the low in-flight CTI levels were measured, further data was taken to measure the impact of straylight on CTI. This data was obtained using an AF variant CCD, 06066-02-02, also irradiated at room-temperature to a fluence of $4 \times 10^9 \text{p}^+ \text{cm}^{-2}$ at the 10 MeV equivalent NIEL dose. This was the same device used to obtain the on-ground CTI measurements used for comparison against in-flight CTI levels (Crowley et al. 2016b). The data was collected at the Gaia Test Bench, currently located at ESTEC in Noordwijk; the test bench was designed to study various effects on the Gaia devices for comparison against measurements from the in-flight CCDs (Crowley 2020).

A dataset was collected consisting of relatively large signal levels that were comparable to the in-flight charge injection levels. From analysis of these results, it was found that increasing the background level would lead to a modest mitigation of CTI. These results were similar to those from the radiation campaigns, where a few $\text{e}^{-}\text{pixel}^{-1}\text{s}^{-1}$ was found to be enough to significantly mitigate the CTI but the addition of increased background resulted in proportionally less mitigation. It was noted that a large back-
ground level, around 1000e-\text{-}, was required for a significant reduction in the fractional charge loss of in-flight-representative charge injection signal levels. It was calculated that for background levels of $3-20$ e$^{-}$pixel$^{-1}$s$^{-1}$, the mitigation was of the order of $4-12\%$ (Crowley et al. 2016b).

From analysis of this data, it was found that the behaviour of the fractional charge loss with background level changed slightly at lower signal levels. This was thought to be due to the presence of a Supplementary Buried Channel (SBC), which would confine a greater proportion of charge to a smaller volume where it would encounter fewer trap defects. In a similar analysis performed on an irradiated RP device (variant 06273-08-01), it was found that a background level of just 100 e$^{-}$pixel$^{-1}$s$^{-1}$ could cause a charge loss mitigation of almost 90\% for a very small signal (149e-\text{-}), completely confined within the SBC. This result implied that the level of CTI mitigation by large background levels would be much greater for signals that lie inside the SBCs as opposed to CIs which would always contain a larger proportion of charge outside the SBC (Crowley et al. 2016b).

### 7.3 Small signals dataset

In order to further investigate the straylight effects on small signals, a second dataset was obtained with the 06066-02-02 AF device. This dataset and the subsequent results are discussed in the remainder of this chapter, ending with a quantification of the straylight effects on CTI. Data was collected at nine different signal levels but this time, relatively smaller signals were collected, some of which would have been fully or partially contained in the SBC, allowing the effects of an SBC to be studied in conjunction. To generate the smaller signals, lower injection-gate voltage levels were applied to the Charge Injections (CIs) as compared to the higher voltage levels used for standard CIs. The small signals were also produced at varying distances from standard CIs to investigate the effectiveness of CIs over large distances.

#### 7.3.1 Data processing

The datafiles were collected in ADU units which required a dark frame subtraction and conversion to units of electrons using the Gaia CCD gain conversion. A number of datafiles were collected at each signal and background level so the signal-to-noise ratio
could be reduced by taking an average. The mean across all the rows and columns of the datafiles was found to further reduce the effects of noise and average out the probabilistic charge release tails. Background subtraction was also performed on all the datafiles that were taken at a given background level.

The data was obtained in a unique format, as illustrated in Figure 7.1. It can be seen that there are three charge injections, each with a small signal, four pixels wide, at different distances from each charge injection. This allows for an investigation of the charge injection effects as well as the straylight effects. Data was collected at nine different background levels and nine different small signal sizes for investigation. The charge injection level was kept fixed throughout all the datafiles, at a value of approximately just less than 17,000 e-, to be representative of the in-flight charge injections. CTI measurements were calculated using both the EPER and FPR techniques, allowing a comparison between these two measurement techniques as well. The EPER CTI measurements use 10 trailing pixels, just like the results from the previous chapter, whereas the FPR CTI measurements only measure the charge lost from the first pixel in relation to the last pixel of signal.

7.3.2 Charge injection results

As a general check of the analysis technique, the CTI measurements of the charge injections were calculated first. Figure 7.2 details both the EPER and FPR measurements of the charge injections, as well as how the CTI changes with background level. As expected, the FPR CTI measurements are larger than the EPER CTI measurements. The charge injections are labelled one to three, corresponding to the order in which they are read-out.

Unsurprisingly, the first charge injection exhibits a larger FPR CTI across all background levels compared to the other two charge injections. After this charge injection, it is very likely that most of the slow-release charge traps are filled, and the greatest possible charge loss has already occurred. As most of the slow traps are still full by the time the other two charge injections are transferred, they undergo a smaller amount of charge loss. The EPER CTI is noted to be approximately equivalent between all three charge injections. As EPER involves the measurement of trailing charge, only the effects of trap defects emitting at equivalent timescales to the pixel transfer time are...
Fig. 7.1 The charge data format used in the straylight analysis. Three charge injections are present, followed by equal-sized small signals, each at a different number of pixel rows from the charge injections. A single pixel row corresponds to a TDI transfer so 1951 pixels refers to a period of \( \sim1.9\) s. Nine different small signal sizes following the charge injections were investigated, in conjunction with nine different background straylight levels. The transfer direction is from left to right.

observed and calculated. This is in contrast to FPR which measures the charge lost due to empty trap defects, regardless of their emission time constant values.

As noted from previous results, straylight causes a noticeable but modest amount of charge loss mitigation on charge injection-equivalent signal levels. A large background of straylight is required to have a much more noticeable effect on the CTI mitigation of the charge injections. These are the same conclusions reached from previous analysis of straylight with charge injections, so these results act as a verification of those conclusions (Crowley et al. 2016b).

7.3.3 TDI distance results

For the next set of results, a single level of small signal charge (850 electrons) was chosen, and the CTI measurements were calculated for the signals at different numbers of pixel rows, or TDI transfers, away from the charge injections, as illustrated in Figure
(a) The FPR CTI with respect to background level charge loss curves for the three different charge injections. It is noted that the first charge injection to be read out experiences the largest amount of charge loss.

(b) The EPER CTI with respect to background level charge loss curves for the three different charge injections.

**Fig. 7.2** The FPR and EPER CTI charge loss curves of the charge injections. In both figures, it is also noted that a large background level is required for a substantial decrease in the CTI level of the charge injection. The charge injection level was $\sim 17,000$ electrons.
(a) The FPR CTI, with respect to background level, charge loss curves for a small signal at three different distances behind a charge injection. It is noted that the closer the signal is to a charge injection, the lower the charge loss it experiences.

(b) The EPER CTI with respect to background level charge loss curves for the three different charge injections. The log-scale has removed the lower half of some of the error bars at the larger backgrounds; they extend as much as their upper halves in linear space.

**Fig. 7.3** The FPR and EPER CTI charge loss curves of the 850 electrons small signal packet, confined within the SBC.

7.1. This allows for a quantification of the effects of charge injections over different distances. The CTI measurements, both FPR and EPER are detailed in Figure 7.3.

Unsurprisingly, the small signal that is only 49-pixel rows away from the charge injection experiences the least of amount FPR. Given that the signal is so close to a charge injection, it is likely that both the fast as well as the slow-release traps are filled from the charge injection so the signal would measure the lowest CTI. By contrast, the fast-release traps that were filled by the charge injections would have emptied after a significant number of pixel transfers, causing the higher FPR CTI of the other small signals. It is noted that despite an increase of almost 1000 pixels from the charge in-
jections, the small signals trailing 1001 pixels and 1951 pixels behind their respective charge injections, manifest similar CTI values. This suggests that after a number of pixel transfers, the charge loss mitigation effect from the charge injections becomes much less substantial.

It is interesting to note that for EPER CTI, the behaviour is slightly different where the signal that was the closest to a charge injection, measures a higher amount of trailing charge. It is hypothesized that this larger amount of trailing charge is due to traps filled by the charge injection still releasing their charge when the small signal is transferred. By contrast, most of the charge injection filled traps should have emitted their captured charge after a larger number of TDI transfers, causing the lower level of EPER CTI in the other small signals. This illustrates a key difference with using different measurement techniques for CTI measurements. The primary goal of charge injections is to keep traps filled and reduce the amount of charge loss in following signals; this objective is being achieved as seen in the top Figure of Figure 7.3.

7.3.4 Small signal results

In the next set of results, the CTI of all the small signal levels at a certain TDI distance from the charge injections are investigated together with respect to the background level. The TDI distance of 1951 pixels, corresponding to a period of ~1.9s, from a charge injection was chosen for this analysis. This is to minimise the impact of the charge injection as much as possible so only the effects of the different background levels can be investigated. This period is also equivalent to the period of the charge injections in the in-flight AF devices (2000 TDI), so the results should be representative of in-flight behaviour (Crowley et al. 2016b). Figure 7.4 details the FPR charge loss curves for the small signals while Figure 7.5 details the EPER charge loss curves. As expected, the FPR measurements are much more substantial compared to the corresponding EPER measurements.

Comparing Figures 7.4 and 7.5, it is noted that the effect of background straylight is much more pronounced on the FPR measurements, and on the charge loss of the signal itself, as compared to the trailing EPER measurements which show a much more modest behaviour of CTI with background. The effects of the SBC, with a capacity of approximately 1000 electrons, are also much more readily apparent in the FPR
Fig. 7.4 The FPR charge loss curves with respect to background straylight level for nine different signal packets, trailing 1951 pixels behind a charge injection. Each datapoint is the result of averaging over many rows and acquisitions. The fall of the FPR values with background level is readily apparent.

measurements as compared to the EPER measurements. As can be seen in Figure 7.4, once the straylight level is high enough, the CTI values for the small signals confined in the SBC become lower than those of the larger signals where a greater proportion of charge lies outside the SBC.

As previously hypothesized, these results confirm that the background straylight causes a much larger charge loss mitigation effect on smaller signals than it does on the larger signals and the charge injections. For the smallest signal investigated in this study (452 electrons), it is found that a background of $\sim 3 \text{ e}^{-}\text{pixel}^{-1}\text{s}^{-1}$ mitigates the charge loss by $\sim 33\%$ whereas for the largest signal level ($\sim 10,000$ electrons), the same background level mitigates charge loss by $\sim 6\%$. The charge loss is less evident when looking at the EPER CTI measurements. Using the same background level of $\sim 3 \text{ e}^{-}\text{pixel}^{-1}\text{s}^{-1}$, the EPER CTI reduces by $\sim 11\%$ for the 452-electron signal and by $\sim 4\%$ for the 10,000-electron signal.

7.4 Straylight Quantification

As has been realised from previous studies and the results of this chapter, background straylight has a mitigating effect on the charge loss of signals. The exact quantification of this straylight factor, however, depends on several factors as established in this chap-
Fig. 7.5 The EPER charge loss curves with respect to background straylight level for nine different signal packets, trailing 1951 pixels behind a charge injection. Each data-point is the result of averaging over many rows and acquisitions. Compared to the FPR measurements, the change in EPER CTI is much more modest as evident in (b), which is a close-up of (a).

Even if the effects of charge injections are ignored, the various factors that alter the amount of measured charge loss mitigation by straylight include the measurement technique (FPR vs EPER), the size of the signal (and whether or not it is confined to the SBC) as well as the level of background straylight itself.

In order to focus the investigations of straylight, two signal levels are chosen to quantify the straylight factor. One is the smallest signal level of 452 electrons which should be representative of the majority of faint signals measured on-board as well as be a quantification of the one of largest possible mitigation effects of straylight. The other signal level chosen is 10,082 electrons which is representative of the average charge
injection level and should provide a comparison point with the extrapolated in-flight CTI measurements at 10,000 electrons from the previous chapter. Table 7.1 details the FPR and EPER CTI values for both these signal levels at the straylight levels studied in this chapter.

Table 7.1 The CTI values for two different signals, measured at nine different background levels using both the FPR and EPER measurement techniques.

<table>
<thead>
<tr>
<th>Signal (e-)</th>
<th>CTI measure -ment</th>
<th>CTI (×10⁻⁵) at Diffuse Optical Background level (e⁻pixel⁻¹s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>452</td>
<td>FPR</td>
<td>8.04</td>
</tr>
<tr>
<td></td>
<td>EPER</td>
<td>2.04</td>
</tr>
<tr>
<td>10,082</td>
<td>FPR</td>
<td>3.95</td>
</tr>
<tr>
<td></td>
<td>EPER</td>
<td>0.58</td>
</tr>
</tbody>
</table>

As noted previously, the median in-flight straylight level is approximately 5e⁻pixel⁻¹s⁻¹; the closest background level in this study to this level was 6.7e⁻pixel⁻¹s⁻¹. Similarly, 90% of the time, the in-flight straylight level is below 20e⁻pixel⁻¹s⁻¹; the closest background level in this study is 18.3 e⁻pixel⁻¹s⁻¹. These are the reference background levels that will be used for the quantification of the straylight factor.

To quantify the straylight factor, the amount of charge loss mitigation, or change in CTI value with respect to the CTI value at 0 e⁻pixel⁻¹s⁻¹ is calculated. This is done for the two different signal levels, using the two different CTI measurement techniques at the two selected straylight levels described previously. Assuming that, for a given set of parameters, the straylight charge loss mitigation is X%, the straylight factor is quantified as 1 + X/100, where the factor represents how much more the CTI would be in the absence of background light. The quantified straylight factors are detailed in Table 7.2.

7.5 Conclusions

This chapter has built on the previous straylight analysis that was performed in Brown (2010) and Crowley et al. (2016b). The work has been extended by investigating the straylight effects on signals of smaller sizes as compared to those that were previously investigated. This was made possible with on-ground data collected at the Gaia test
Table 7.2 The straylight factor for two different signal levels at two different background levels using two different CTI measurement techniques. The factor represents how much more the CTI would be in the absence of background light.

<table>
<thead>
<tr>
<th>Signal (e-)</th>
<th>CTI measurement</th>
<th>CTI factor at Diffuse Optical Background (e − pixel⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6.7</td>
</tr>
<tr>
<td>452</td>
<td>FPR</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>EPER</td>
<td>1.17</td>
</tr>
<tr>
<td>10,082</td>
<td>FPR</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>EPER</td>
<td>1.07</td>
</tr>
</tbody>
</table>

bench at ESA, ESTEC. The results of the impact of straylight on signals has not differed significantly from the previous results.

Using artificial light is a CTI mitigation technique used in previous studies and other space missions. Although an artificial light source was not used on-board Gaia, the straylight levels in-flight are strongly suspected to have served the same purpose and are partially responsible for the lower-than-predicted measured in-flight CTI levels. While the impact of straylight has been studied and detailed in other studies, as previously mentioned, this chapter investigated the mitigation of charge loss of small signals in particular. The straylight factor has been quantified with respect to several different parameters. These straylight factors will be re-introduced and analysed with other factors in Chapter 10 of this thesis.
CHAPTER 8

Radiation dose

8.1 Introduction

The difference in radiation dose experienced between the in-flight and on-ground CCDs is hypothesised to be a significant factor in the difference in observed CTI levels between in-flight and on-ground CCDs. As noted from Figure 6.20 of Chapter 6, after more than 6 years in orbit, the in-flight CTI is still an order of magnitude lower than the CTI measured from the pre-launch on-ground tests. Using the on-ground charge data from chapter 7 and data from some of the in-flight CCDs, another comparison can be made as detailed in Figure 8.1, comparing the EPER CTI between the datasets. There is a difference in the time after charge injections for the in-flight and on-ground data. The in-flight data was taken from CIs spaced by $\sim 0.4s$ and the on-ground data was taken from a signal $\sim 1.9s$ after a CI. Regardless, there is still a substantial difference in CTI between the datasets.

The on-ground CCDs were irradiated to a dose of $4 \times 10^9 \text{ p}^+ \text{ cm}^{-2}$ at the 10 MeV equivalent NIEL dose. While a 20% safety margin was applied to this irradiation level, the on-ground CTI is still measurably larger than the in-flight CTI after the safety margin is accounted for (Crowley et al. 2016b).

8.2 Solar activity and proton models

As detailed in Chapter 4 and re-introduced here, the baselines for the on-ground irradiations were taken from the predicted level of solar activity as measured during the early pre-flight stage of the Gaia mission in 2006. At that point, Gaia was predicted to have an earlier launch date of December 2011. Astrium, now Airbus Defence and Space, predicted the radiation dose across the focal plane using a computer model of the Gaia
Fig. 8.1 A comparison of the EPER CTI measurements from a number of in-flight devices at two different points in the mission and from the irradiated AF 06066-02-02 variant device detailed in Chapter 7. The on-ground data was taken from the large signal sizes, largely outside the SBC, trailing 1951 pixels behind charge injections.

spacecraft in a software package called Systema-Dosrad. The reference model used to simulate the long-term solar proton effects was the JPL-1991 model; for a launch in December 2011, 4 years of solar maximum activity were used. Solar Cycle 24 was predicted to have been very active, and the predictions were made at the 90% confidence level, which was the European Space Agency (ESA) standard at the time. This meant that 90% of the time, the actual radiation dose would have been less than the predicted outcome (Kohley et al. 2014).

As discussed in Chapter 4, the radiation dose analysis measured a different amount of NIEL dose for the different devices across the focal plane. Devices further from the centre and devices with instruments set-up in front of them were predicted to receive a lower dose. The largest 10 MeV equivalent NIEL dose measured across the focal plane was on the AF devices, with a calculated cumulative mean dose of $3.11 \times 10^9$ p$^+$ cm$^{-2}$. As noted previously, higher energy Galactic Cosmic Rays (GCRs) were neglected in the radiation dose analysis due to the predicted high level of solar activity (Kohley et al. 2014).

As time went on during the pre-flight stage, more predictions were made about a weaker solar cycle for the Sun. Figure 8.2 details the highest and lowest predicted activity levels of Solar Cycle 24 as made in 2009, as well as the actual activity, produced
using data from the NOAA Space Environment Services Centre (NOAA Space Weather Prediction Center 2009, 2020). When looking at the mean sunspot number, it is noted that the solar activity has been closer to the lowest prediction level than to the highest. Gaia’s launch date was also pushed forward to December 2013 and the spacecraft has been granted a mission extension to 2025, well past the original mission plan. The planned and current timelines are also detailed in Figure 8.2; given the amount of fuel on-board and the low levels of CTI, Gaia could continue operating into 2025 which would be more than double the original mission timeline (Pancino 2020).

**Fig. 8.2** The monthly mean sunspot number counts for the activity of the Sun from 2000 to 2020 compared with the high and low predictions of Solar Cycle 24 as well as the mean prediction for Solar Cycle 25 (proton flux source data: NOAA Space Environment Services Centre)

Part of the reason for the predicted higher level of activity was due to the use of the JPL-91 model. This model was developed in the past and uses data from solar cycles 20-22 to make its predictions (Feynman et al. 1993). By contrast, the SAPPHIRE model is a much more recently developed solar proton model, that uses 40 years of data in its implementation and is the current recommended model to use for ESA, having been validated against other datasets. The SAPPHIRE model is known to predict reduced fluences as compared to the JPL model at most energy levels, attributed to a difference in modelling techniques (Jiggens et al. 2017, 2018). Running a SAPPHIRE simulation
with a simple model of 11mm of spherical Aluminium with Gaia’s mission parameters returns a 10 MeV equivalent NIEL dose of $1.8 \times 10^9 \text{p}^+ \text{cm}^{-2}$ at the 90% confidence level which is almost a factor of two less than the original predicted dose across the AF devices.

A limitation of these proton models is that they work with confidence levels; the quoted values are a probability rather than a real, measured dose value. To really understand and quantify the impact of radiation dose, the best way forward would be to model and quantify the trap defect landscape. There is only so much information that can be obtained from the solar proton models because predicting the solar activity is a difficult and randomised task.

A technique that can be applied to compare and measure the radiation dose between the in-flight and on-ground devices would be to calculate the exact numbers of different traps in the in-flight and on-ground data and compare the trap densities. Looking at the radiation dose this way means that the impact of other sources, such as GCRs, get absorbed into the trap defect numbers. As discussed in previous chapters, the lower level of solar activity means that the contribution from GCRs would be more substantial than the zero-level used in the pre-flight predictions.

An ideal method to analyse the trap landscapes would be to perform trap-pumping on the CCDs. Trap-pumping is an analysis technique that allows for the probing of almost all the radiation-induced trap defects detailed in the literature by controlling the temperature of the device and the clocking speed used. Trap pumping also reveals the locations of different trap defects in the CCD itself (Hall et al. 2014). Unfortunately, trap-pumping could not be performed in the context of this thesis. The in-flight CCDs continuously read-out in Time-Delayed Integration and the spacecraft was not developed with an LED or the necessary electronics to allow for trap-pumping to be performed. The covid-19 pandemic also meant that it was not able to perform trap-pumping with on-ground devices due to travel and social distancing restrictions at the time.

The next best solution was to try and model the charge data that was available with different charge transfer models. These include the Charge Distortion Model (CDM), briefly mentioned in Chapter 3, through the simulation toolkit called Pyxel, and the Centre for Electronic Imaging CCD Charge Transfer Model (C3TM). The exact pro-
cedures and methodology described in this chapter has, to date, not been performed before and not in the context of Gaia. The results of this chapter not only allow for an eventual comparison of the radiation dose in the in-flight and on-ground devices via the modelled trap landscapes, but also allow for an evaluation of the simulation models used and a detailed look into the trap landscapes of the irradiated Gaia CCDs.

8.3 CDM re-introduction

The charge transfer model first used to model the data, was the Gaia Charge Distortion Model (CDM), previously detailed in Chapter 3 and re-introduced here. CDM was developed during Gaia’s pre-flight stage as a fast forward-modelling technique to be used in the Gaia data processing pipeline to calibrate the effects of radiation-induced trap defects. As mentioned in Chapter 4, a forward modelling approach was chosen over a corrective approach in the development of CDM to preserve the noise properties of the data and have the flexibility to treat dispersed spectra and non-point source objects in the same way as isolated single stars (Short et al. 2013).

As the primary focus was fast, computational speed, CDM was designed to be empirical while being flexible and realistic enough to reproduce the distortion effectively. While a model based on more physical parameters would have provided more physical results, it would have been computationally more expensive. This meant that using CDM to model the datasets would produce results that may not necessarily be completely physically realistic as those objectives go beyond the goal of what CDM was originally designed to do. Nevertheless, CDM would still reveal useful insights into the nature of the radiation-induced trap defects in the Gaia CCDs and can be used as a reference point for other investigations (Short et al. 2013).

To model CTI effects, CDM takes a number of input parameters such as emission time constants and trap densities of trap defects, a beta parameter that describes the signal’s volume-density relationship and the operating parameters of the CCD. Using these parameters, input data can be run through CDM to produce CTI-distorted data. The model was designed by DPAC to be used in a scheme where the parameters of CDM and a given CTI-free image could be iteratively adjusted until CDM could produce a predicted, distorted image that best matches a set of observed data. For this thesis, the data was initially modelled using Python’s built-in minimisation functions, however
these results revealed a degeneracy where multiple different solutions and parameter sets were found that could model a dataset. To account for this degeneracy, a modelling software framework called Pyxel was chosen to be used in conjunction with CDM.

8.4 Pyxel

Pyxel is a python simulation toolkit, developed collaboratively between the European Space Agency (ESA) and the European Southern Observatory (ESO). Its origins stem from the fact that the latest generations of instruments and detectors have been pushing their technical capabilities closer to their theoretical limits and that advances in computing have led to more accurate simulations of different levels of instrument design and operation. Pyxel was designed to combine all the different instrument models and simulations, detailed in the literature, so that they can be used in conjunction and form a complete end-to-end detection chain simulation from optical effects to readout electronics (Prod’homme et al. 2020).

8.4.1 Calibration mode

Pyxel has a number of different running modes so researchers can perform different analyses. These include a “single” mode which performs a single pipeline run for a quick health check and a “parametric” mode where the detection pipeline is run multiple times over a range of parameters to perform sensitivity analysis (Prod’homme et al. 2020). For the purposes of modelling Gaia’s in-flight and on-ground data, Pyxel’s “calibration” mode was used in this investigation.

In Pyxel’s calibration mode, input and target datasets are supplied by the user; built-in optimization algorithms and user-defined fitness functions are then utilised to find the optimum model or detector parameters that best model the input data to the target data. Pyxel uses an implementation of ESA’s Python Parallel Global Multiobjective Optimizer (PyGMO), a suite of optimisation algorithms, to help achieve its calibration mode objectives (Izzo 2012). In this investigation, charge data was modelled with CDM using Pyxel’s calibration mode, to find the best fit trap defect parameters. With the help of PyGMO, CDM’s degeneracy should be mitigated as the algorithms should find the solutions with the best-fit.

Figure 8.3 outlines the results of a calibration run as a champion heatmap, where the
model was made to fit to four different emission time constants. In calibration mode, a number of different values are tried before the simulation starts to converge towards values that produce better “fitness”. To model the Gaia datasets, Pyxel was made to find the emission time constants and effective trap densities that would best replicate and fit the data. The signal volume-density beta parameter was chosen to be kept fixed to reduce the number of free parameters and computation time; a value of 0.52 was chosen based on the results from Chapter 6.

![Champion heatmap from a Pyxel calibration run](image)

**Fig. 8.3** A champion heatmap from a Pyxel calibration run where the model fits to four different emission time constants.

### 8.5 Pyxel modelling

#### 8.5.1 Trap defects

As detailed in Chapter 2, a number of radiation-induced trap defects can be formed in CCDs which can affect the CTI of the devices. The trap defects can be complexes between atoms like oxygen, phosphorus and carbon, or can be stable combinations of vacancies and interstitials and are named based on their inherent properties. They each have unique energy levels which means they all interact with signals differently
depending on the CCD operating temperature and transfer speed (Bush et al. 2021, Buggey et al. 2022). Figure 8.4 details the trap defect landscapes for an irradiated CCD204 at three different temperatures.

![Figure 8.4](image)

**Fig. 8.4** Trap landscapes of an irradiated CCD204 at three different temperatures; this is a replication of Figure 3 of Buggey et al. (2022). It can be seen that the trap defects have unique, temperature dependent emission time constants and are formed in different proportionate amounts.

There are a number of radiation-induced trap defects detailed in the literature (Bush et al. 2021), but given Gaia’s operating temperature and TDI clocking speed, only some of these will produce observable effects in the charge data. To get an understanding of the potential Pyxel results and the most likely observed and modelled trap defects, simulations were performed in CDM. For these CDM simulations, a block of charge of 10,000 electrons was taken as an input and run through a fixed density \((1 \times 10^{10} \text{ traps cm}^{-3})\) of different trap defects in different simulation runs. For each different simulation run and corresponding trap defect, the EPER CTI was calculated with the trailing 10 pixels after the charge block as well as the percentage charge loss which was taken as the amount of charge lost from the first five pixels as a function of the 10,000 electron input signal. The results of the simulations are detailed in Figure 8.5 and Table 8.1; the emission time constants were calculated using the Shockley-Read-Hall equations and literature values for the trap defect parameters (Bush et al. 2021,
In previous studies that have compared differences between cryogenic and room-temperature irradiations, a group of defects are known to be produced from cryogenic irradiations with emission time constants that lie between the Divacancy (VV$^{--}$) and “Unknown” trap defect peaks in a trap landscape plot. Compared to the other radiation-induced defects that have relatively well-defined energy levels and cross-section values, these defects have a large spread of values on a trap landscape plot which makes it difficult to accurately obtain values for the energy levels and cross-sections. This spread of traps is referred to as the continuum; studies have shown that with a large enough temperature anneal, some of the defects might migrate from the continuum to the divacancy peak (Buggey 2021, Parsons et al. 2021).

Given the operation conditions and environment of the Gaia spacecraft, it is highly likely that the in-flight data would be modelled with a larger number of continuum defects as compared to the on-ground data. In order to model the continuum, a set of values are used that were obtained from simulation work performed on irradiated Euclid devices using a simulation model called the Centre for Electronic Imaging CCD Charge Transfer Model (C3TM), which will be discussed in more detail in section 8.6. It should be noted that the Continuum values found from C3TM and used in Table 8.1 are best-fit values to physical measurements so should be taken with some caution (Skottfelt et al. 2017).

### Table 8.1
The literature parameter values of the radiation-induced trap defects, their corresponding emission time constants at Gaia’s TDI operating speed ($982.0 \mu$s) and temperature (163.15 K), the 10-pixel EPER CTI and percentage charge loss values for a 10,000-electron signal as simulated and calculated in CDM.

<table>
<thead>
<tr>
<th>Trap Defect</th>
<th>$\sigma_e$ (cm$^2$)</th>
<th>E (eV)</th>
<th>$\tau_e$ (s)</th>
<th>EPER CTI (10,000 e-)</th>
<th>Percentage charge loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VV$^{--}$</td>
<td>$(2.6 \pm 0.5) \times 10^{-15}$</td>
<td>0.225 ± 0.005</td>
<td>3.66 × 10$^{-5}$</td>
<td>7.34 × 10$^{-11}$</td>
<td>3.30 × 10$^{-11}$</td>
</tr>
<tr>
<td>Si-E</td>
<td>$(3.7 \pm 0.8) \times 10^{-14}$</td>
<td>0.475 ± 0.015</td>
<td>66.71</td>
<td>5.85 × 10$^{-9}$</td>
<td>17.93</td>
</tr>
<tr>
<td>VV$^-$</td>
<td>$(2.0 \pm 1.0) \times 10^{-15}$</td>
<td>0.42 ± 0.01</td>
<td>24.68</td>
<td>1.58 × 10$^{-8}$</td>
<td>17.93</td>
</tr>
<tr>
<td>“Unknown”</td>
<td>$(8.7 \pm 0.7) \times 10^{-15}$</td>
<td>0.37 ± 0.01</td>
<td>0.162</td>
<td>2.32 × 10$^{-6}$</td>
<td>17.8</td>
</tr>
<tr>
<td>Si-A</td>
<td>$6.1 \times 10^{-15}$</td>
<td>0.165</td>
<td>1.07 × 10$^{-7}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Continuum</td>
<td>$5.0 \times 10^{-16}$</td>
<td>0.27 ± 0.05</td>
<td>1.94 × 10$^{-3}$</td>
<td>2.23 × 10$^{-5}$</td>
<td>10.08</td>
</tr>
</tbody>
</table>
Fig. 8.5 CDM simulations of a 10,000-electron signal as it is transferred and distorted through fixed densities \((1 \times 10^{10} \text{ traps cm}^{-3})\) of known radiation-induced trap defects from literature.


From the results in Table 8.1 and Figure 8.5, it can be seen that the continuum produces the largest amount of CTI with respect to Gaia’s operating parameters. However, due to the large spread of emission time constant values it may be difficult to accurately identify its effects in the charge calibration data. With respect to the other radiation-induced trap defects, the “Unknown” is next defect that produces the largest CTI contribution. The A-centre emits too fast in Gaia’s TDI clocking speed to produce any noticeable effects. While the single Vacancy and E-centre cause charge loss, it should be noted that these traps are very slow-emitting with respect to Gaia’s TDI clocking speed. The charge tails of these CDM-simulated traps are sub-electron so they are unlikely to be responsible for any observable effects in the charge tails of the charge calibration data. Given that the charge tail is being investigated in the simulations and that straylight and charge injections have been noted to be sufficient enough to fill in the slower traps, the single Vacancy and the E-centre are ignored for rest of the simulation analysis.

For the Pyxel calibrations, the parameter range for fitting the emission time constants was restricted to be between \(1 \times 10^{-4} \text{s}\) and \(1.0 \text{s}\). Below \(1 \times 10^{-4} \text{s}\), the emission time constants would be too fast to produce any charge tails in CDM whereas emission time constants above \(1.0 \text{s}\) would be so slow that nonsense values could be fitted.
that don’t actually model the data. Figure 8.6 below justifies this choice of parameters; it illustrates the charge tails formed from CDM simulations with range of different emission time constants at the same trap densities.

Fig. 8.6 The charge tails for a range of different emission time constants, as simulated in CDM. The trap density was kept the same between all the different simulations (1 × 10^{10} traps cm^{-3}).

8.5.2 Data processing

To investigate the parallel CTI, input and target datasets were extracted from in-flight and on-ground charge calibration data to be modelled by Pyxel. For the in-flight data, the charge calibration data as detailed in Chapter 6 was used from a CCD located towards the centre of the Gaia focal plane (AF8 Row 6); this is because this CCD would have experienced a larger dose and a larger increase in CTI. The charge calibration data from May 2014 was taken as the input dataset and the data from December 2019 was taken as the target dataset so the modelling should reveal the trap defects formed over 5 years of radiation damage. This in-flight data was taken at the stable operating temperature of 163.15K, well after the on-board heating events.

The data used for the straylight measurements described in Chapter 7 was used to represent the on-ground data. For the target datasets, the data was used for the small signals, trailing 1951 pixels behind a charge injection at a background level of 0 e^{-pixel^{-1}s^{-1}}. Unfortunately, there was no equivalent pre-irradiated data available.
that could be used for the input datasets so “artificial” input data was created by taking the target data and removing the charge tails. Although the on-ground CCD was irradiated at room temperature, the CI measurements were taken when the device was cooled down to 163K so the on-ground CTI measurements should be comparable to the in-flight measurements.

The in-flight and on-ground charge calibration data described was in the format of two-dimensional FITS image files. Before the data was used in Pyxel’s calibration mode, the FITS files were made into one-dimensional text files to speed up the calibration process. These one-dimensional files were found by taking the original FITS files and modifying the data to find, not only the mean of the charge injections and trailing pixels in a single column, but also the mean of the data in the columns themselves. After this, the background was taken as the mean of the last 50 pixels and subtracted from the entire data. Background light was present in the in-flight datasets; it is known that background signal will have a small but measurable impact on CTI. Unfortunately, there is little more that can be done outside of background subtraction to remove these non-linear effects so for the modelling work, the background effects on the in-flight CTI are neglected. The entire data processing procedure is outlined in Figure 8.7.

Two complications were noted during the data processing, one was with respect to inconsistent charge injections and the second was with the landscape of pre-flight defects. For the in-flight data, the target charge injection levels did not exactly match the input charge injections. It is hypothesized that the irradiations may be affecting or damaging the charge injection structures in some way; this effect has been noted in other studies (Buggey 2022). It was assumed that this difference would have an inconsequential effect and the data was not edited or changed. The pre-flight defects are a trickier problem to deal with. The lack of pre-irradiated on-ground data means the pre-flight trap landscape cannot be modelled and effects of pre-flight defects will be present in the data. Given the densities of pre-flight defects in the literature, it is assumed that the effects of radiation-induced trap defects will dominate over the effects of pre-flight defects (Bush et al. 2021).
Fig. 8.7 The data processing steps which illustrate how the 2-D FITS image files were reduced and simplified down to 1-D image lines.

8.5.3 On-ground data - Modelling results

Using the input and target on-ground datasets as described in the previous section, Pyxel calibration runs were performed to get the best-fit CDM trap parameters that would describe the increase in parallel CTI between the two datasets. Three traps was found to be the ideal number of traps to be input into the model to obtain the best fit. Modelling three traps produced better fitness values than two traps and modelling more than three traps resulted in over-fitting where the same emission time constant would be fitted twice.

Figure 8.8 and 8.9 detail the fitness champion heatmap plots of the three fitted emission constants and trap densities respectively. The better the fitness, the lower the fit-
ness value and the greater the occurrence with the occurrence of each value/fitness pair shown in colour. It is noted that Pyxel was able to calibrate towards three distinct emission time constants that do not overlap with each other. This lends credence to the idea that three traps in CDM are sufficient to model the on-ground Gaia data. The exact values of the fitted emission time constants and densities are given in Table 8.2. As detailed in Chapter 7, the data for the on-ground data was collected at 163 K after the CCD was irradiated at room temperature.

Table 8.2 Best fit CDM trap parameters for the on-ground charge calibration data, as produced by Pyxel’s calibration mode.

<table>
<thead>
<tr>
<th>Trap No.</th>
<th>$\tau_e$ (s)</th>
<th>Trap density (traps cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$7.9 \times 10^{-4}$</td>
<td>$1.4 \times 10^9$</td>
</tr>
<tr>
<td>2</td>
<td>$1.4 \times 10^{-2}$</td>
<td>$1.5 \times 10^9$</td>
</tr>
<tr>
<td>3</td>
<td>$1.4 \times 10^{-1}$</td>
<td>$5.7 \times 10^9$</td>
</tr>
</tbody>
</table>

Fig. 8.8 A champion heatmap produced by Pyxel’s calibration mode that displays the best fitted emission time constant values that model the on-ground data.
8.5.4 In-flight data - Modelling results

Using the May 2014 data as the input dataset and the December 2019 data as the target dataset, Pyxel calibrations were performed to model the parallel CTI of the in-flight data. In order to compare the results of the calibrations of the in-flight and on-ground datasets, the in-flight data was also calibrated to fit to three different trap species. Coincidentally, it ended up being the case that three traps were enough to adequately fit to the in-flight data as well. Figures 8.10 and 8.11 detail the fitness heatmap plots of the three fitted emission time constants and their densities for the in-flight data. As was the case for the on-ground data, the datasets are calibrated to three distinct emission time constants. The exact values of the fitted emission time constants and densities are given below in Table 8.3. For these in-flight results, a very small density of a 4th trap defect was present in CDM ($\tau_e = 9.4 \times 10^{-4}$s ($3.9 \times 10^7$ traps cm$^{-3}$)) to represent a pre-flight defect. This trap adds $\sim 1.5$ electrons to the charge tail which was found to be inconsequential to the final results. As detailed in Chapter 6, the in-flight data was collected at the mission’s operating temperature of 163.15 K.
Fig. 8.10 A champion heatmap produced by Pyxel’s calibration mode that displays the best fitted emission time constant values that model the in-flight data.

Fig. 8.11 A champion heatmap produced by Pyxel’s calibration mode that displays the best fitted effective trap density values that model the in-flight data.
Table 8.3 Best fit CDM trap parameters for the in-flight charge calibration data, as produced by Pyxel’s calibration mode.

<table>
<thead>
<tr>
<th>Trap No.</th>
<th>$\tau_e$ (s)</th>
<th>Trap density (traps cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$4.7 \times 10^{-4}$</td>
<td>$6.9 \times 10^8$</td>
</tr>
<tr>
<td>2</td>
<td>$3.6 \times 10^{-3}$</td>
<td>$2.5 \times 10^8$</td>
</tr>
<tr>
<td>3</td>
<td>$2.3 \times 10^{-2}$</td>
<td>$4.2 \times 10^8$</td>
</tr>
</tbody>
</table>

8.5.5 On-ground and in-flight results comparison

When comparing the results of Table 8.2 and 8.3, it is noted that while the emission time constants between some of the results for the in-flight and on-ground data have the same orders of magnitude, the exact, fitted values are not the same. As discussed previously, CDM fits to an exact emission time constant value whereas in reality, each trap defect has a range of emission time constant values, peaking at a specific value at a given temperature. It is therefore not surprising that the fitted emission time constant values are not quite the same between the in-flight and on-ground results.

Due to the way it was designed, CDM does not simulate all the physical effects and it is likely that the fitted traps are the best fits from a collection of multiple physical trap defects which are producing non-linear effects. It can be extrapolated from this that some of the fitted emission time constants in the in-flight and on-ground datasets being the same order of magnitude would indicate that similar physical trap defect properties are replicated in the fitted CDM parameters. However, this would also indicate that the fitted trap densities are likely not to be physically realistic but an amalgamation of several different effects, as mentioned previously. The trap densities are considered as “effective” trap densities.

For further investigation, the charge tails produced from the fitted trap defects are simulated and analysed. Figure 8.12 illustrates the general effects of trap defects on a charge injection (CI), or block of charge. It can be seen that trap defects capture charge from the first pixels of the CI and emit charge after the CI has been transferred, leading to the formation of a deferred charge tail. By comparing the charge tails between different datasets and simulations, it becomes possible to extrapolate more specific details of the trap defects and understand their behaviour. The CIs will not be shown in the figures detailing the charge tails for visual clarity but it is understood that they precede the charge tails.
Fig. 8.12  A charge injection (CI) block after it has been transferred through a CCD with trap defects. Charge is lost from the first few pixels and a deferred charge tail is formed behind the CI from the emission of charge from trap defects. The deferred charge tails will be investigated further in this chapter. The effects seen in this figure are exaggerated and not to scale.

CDM was designed for fast forward-modelling in order to accurately model and describe given datasets. Figure 8.13 illustrates a charge tail of the Pyxel on-ground trap parameters simulated in CDM plotted against a charge tail from the on-ground data while Figure 8.14 does the same for the in-flight data. The $\chi^2$ values that were calculated between the charge tails of the simulated data and the experimental data was 0.84 for the on-ground results and 17.35 for the in-flight results. Given that the behaviour in the charge calibration data is accurately modelled, as indicated by the relatively low $\chi^2$ values, the primary objectives of CDM have been met. It is noted that the CDM simulation of the in-flight data underestimates CTI as compared to the actual in-flight data; this is also noted by the relatively higher $\chi^2$ value. This is thought to be because the Pyxel parameters obtained best describe the trap defects formed between April 2014 and December 2019. They likely do not account for the trap defects already present in the April 2014 data, noted to cause a small but finite amount of CTI, as discussed in Chapter 6.

While the Pyxel-fitted CDM parameters replicate the datasets relatively accurately,
Fig. 8.13 Charge tails from one of the charge injection signal levels in the on-ground data and from a CDM simulation using the trap defect properties obtained from Pyxel’s calibration of the on-ground data; the $\chi^2$ value between these two charge tails is 0.84.

Fig. 8.14 Charge tails from one of the charge injection signal levels in the in-flight data and from a CDM simulation using the trap defect properties obtained from Pyxel’s calibration of the in-flight data; the $\chi^2$ value between these two charge tails is 17.35.
they do not necessarily provide realistic answers for the trap landscapes. However, even though the results may not be physically accurate, they are accurate representations of real, physical effects. To take this investigation further and get a better understanding of the trap landscape, the CDM results obtained from Pyxel are used as a starting point to compare against C3TM simulations.

8.6 C3TM modelling

8.6.1 Introduction

C3TM, or the CCD Charge Transfer Model is designed for simulating charge transfer in a radiation damaged CCD. It is a Monte Carlo model that is based on Shockley-Read-Hall theory and mimics the physical properties of a CCD as accurately as possible. To achieve a high level of accuracy, it uses device specific charge density simulations as a direct input, generated with professional TCAD software. It runs on a sub-electrode level and can simulate different trap defects, each with their own emission time constant, physical location in the CCD and other properties (Skottfelt et al. 2017, 2018).

Compared to CDM, C3TM is computationally more expensive but is able to simulate physical effects more thoroughly and reproduce results from experiments more accurately. Previous work has revealed more details about the nature of charge capture and emission by comparing the results of C3TM simulations with laboratory results (Skottfelt et al. 2017, 2018). Figure 8.15 shows a charge tail from a single trap defect, as simulated in both CDM and C3TM. It can be seen that a single trap species is modelled as a single exponential in CDM. However, C3TM can simulate more physical effects such as charge recapture, which results in an extended charge tail. Two different exponential fits are required to model the charge tail of a single trap species. This would indicate that using CDM, Pyxel could fit to two different trap species when in reality, the effects of only one is being observed.

C3TM is also able to simulate a variety of different charge transfer schemes such as multi-level clocking, and trap pumping. It can also simulate charge injections, whose parameters can be defined by the user. To obtain results that best describe and replicate the charge calibration data, C3TM simulations were run that were set at the same charge injection scheme and parameters as the in-flight and on-ground datasets.
Fig. 8.15 Charge tails produced from a single trap species as simulated by (a) CDM and (b) C3TM. Fits are also made at different points in the C3TM charge tail, illustrating more complicated behaviour compared to a single exponential.

As mentioned previously, C3TM is much more computationally expensive and trying to fit trap defect parameters directly to the charge data would be a very time-consuming process. However, as the CDM results accurately model the CTI effects as given by the relatively low $\chi^2$ values between the simulated and real data, they could be used as a starting point to perform C3TM simulations; this helps save on computational time. To understand the trap landscapes that needed to be generated with C3TM simulations, they were first compared against CDM simulations of the parameters obtained from Pyxel.

Figures 8.16 and 8.17 detail the charge tails formed for a 10,000-electron block of charge, as simulated in CDM using the trap defect results from Pyxel’s calibration mode in Tables 8.2 and 8.3. Figure 8.16 illustrates the charge tails from the fitted on-ground data and Figure 8.17 illustrates the results from the fitted in-flight data. As mentioned before, none of these are necessarily simulations of individual trap defects but they are accurate representations of real physical effects from multiple defects. These results can be taken as a reference point and compared against charge tails produced in C3TM. The C3TM trap densities which would best match the CDM results should be close to the true trap densities present in the in-flight and on-ground data.
8.6.2 Data generation and processing

There were limitations to using C3TM simulations in this work. The model was written and designed to simulate effects in the Euclid CCDs (CCD273). While the code was written so that it could be easily be adapted to detectors for other instruments, accurate semiconductor simulations would still be required. Unfortunately, Silvaco semiconductor simulations of the Gaia CCD (CCD91-72) could not be generated or used for this study due to time constraints. The C3TM operating parameters and device geometrical properties were modified to match those of Gaia’s parameters as best as possible. While these results may not be able to give an exact representation of the trap defect effects in the Gaia CCDs, they should at least be accurate enough to allow a comparison point and infer details about the true trap landscapes.

Given Gaia’s TDI clocking speed, the CDM simulations detailed earlier in this chapter and the results from other studies, the likely trap defects responsible for the charge
The charge tails following a 10,000-electron signal, as simulated in CDM, of the three fitted emission time constants and trap densities from the in-flight data calibration.

tail CTI effects in the Gaia data are the silicon divacancy, the “unknown” defect and the continuum. By inputting a charge injection scheme into C3TM, identical to that of the in-flight and on-ground data, the charge tails from each of these different trap defects can be simulated. By comparing the C3TM charge tails to the charge tails produced in CDM from the Pyxel calibration results, it is possible to extrapolate the most likely trap defect landscapes. Due to the fact that charge emission is a probabilistic effect, and this is accurately simulated in C3TM, a number of simulations are made, and the median is found between them. This produces an averaged C3TM charge tail which can be compared with the charge tails of Pyxel. A chi-squared goodness of fit statistic is used to compare the charge tails generated in CDM with those from C3TM.

C3TM uses parameter values of the properties of the trap defects to accurately simulate their behaviour. For these simulations, the charge property values were taken from various studies (Bush et al. 2021, Skottfelt et al. 2018). It should be noted that the continuum’s properties are not physical but rather a set of best-fit values given comparisons.
to experimental data. The values used for the divacancy, continuum and the “unknown” are detailed in Table 8.4 below.

**Table 8.4** Details of the trap species used in the C3TM charge tail simulations. The emission time constants are calculated by C3TM at Gaia’s operating speed and temperature given the other trap properties.

<table>
<thead>
<tr>
<th>Trap</th>
<th>$\tau_e$ (s)</th>
<th>E (eV)</th>
<th>$\sigma_e$ (cm$^2$)</th>
<th>$\sigma_c$ (cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$VV^{--}$</td>
<td>$3.09 \times 10^{-5}$</td>
<td>$0.235 \pm 0.005$</td>
<td>$2.6 \times 10^{-15}$</td>
<td>$5 \times 10^{-16}$</td>
</tr>
<tr>
<td>“unknown”</td>
<td>$1.62 \times 10^{-2}$</td>
<td>$0.35 \pm 0.003$</td>
<td>$8.7 \times 10^{-15}$</td>
<td>$1 \times 10^{-17}$</td>
</tr>
<tr>
<td>Continuum</td>
<td>$1.94 \times 10^{-3}$</td>
<td>$0.27 \pm 0.05$</td>
<td>$5 \times 10^{-16}$</td>
<td>$1 \times 10^{-17}$</td>
</tr>
</tbody>
</table>

**8.6.3 Trap identification and comparison**

The goal of the analysis was to find C3TM trap defect parameters whose charge tails would give the lowest chi-squared goodness of fit values when compared to CDM charge tails. These trap defect parameters could then be compared to the physical charge tails and further C3TM simulations could be run to find the trap defect parameters that best match the experimental charge tails. While it would have been feasible to fit C3TM to the experimental charge tails directly, finding the best fit trap parameters would have been a lot more time consuming. This is because multiple different trap density solutions can produce very similar effects and it would be difficult to work out which set of results would be representative of the true trap density. By fitting to the CDM charge tails first, an initial set of results for individual trap defects can be obtained which reduces the number of C3TM simulations that will need to be run.

Before this could be achieved, some prior work needed to be performed in order to work out the optimal C3TM and CDM simulations to use and perform that would provide the best-fit results. Note that the goal is to find the best-fit and not necessarily a perfect fit.

Figure 8.18 details the charge tail produced from a C3TM simulation of a charge injection with a specific density of the divacancy with the fastest fitted on-ground trap from Pyxel ($\tau_e = 7.9 \times 10^{-4}$s) plotted alongside it. It can be seen that the Divacancy tail is similar to the tail produced from the fast defect. The $\chi^2$ value between these two tails was 40.25; while this is relatively high, analysis of the charge tails of other defects has revealed that no other radiation-induced trap defects produce similar such
tails for Gaia’s operating parameters. Therefore, it is likely that the Pyxel fitted $10^{-4}\text{s}$ traps are manifestations of the divacancy trap defect. Any discrepancies could be due to fitting imperfections or due to the combination with another trap defect of much lower densities, like the continuum.

**Fig. 8.18** A comparison of the charge tails, for a 13,370-electron signal, between a CDM simulation of the fastest on-ground calibrated trap defect and a C3TM simulation of a density of Divacancy; $\chi^2 = 40.25$.

Figure 8.19 details the charge tail produced from a C3TM simulation of the “unknown” with the CDM simulated charge tails from the other two fitted on-ground trap defects from the Pyxel calibrations plotted alongside it, both separately and together. In real CCDs, recapture effects take place in the charge tail which causes the charge tail to become elongated; an effect that is accurately replicated in C3TM. It can be seen that while neither the $10^{-2}\text{s}$ nor the $10^{-1}\text{s}$ order of magnitude traps accurately replicate the charge tail of the “unknown”, collectively, they can provide a much closer match. The $\chi^2$ value between the two combined CDM charge tails and the C3TM tail is 1.58. In the absence of other radiation-induced trap defects that can produce these charge tails, it is
likely that Pyxel fits two different trap species as a manifestation of the “unknown”’s physical effects. This is identical to the charge-recapture behaviour that was observed in Figure 8.15(b).

**Fig. 8.19** Simulated charge tails following a 10,000-electron charge block as produced in CDM and C3TM. The CDM charge tails are made using the emission time constants and effective trap densities modelled from Pyxel’s calibration of the on-ground data while the C3TM charge tail uses a given density of the “Unknown” trap defect.

After the “unknown” and divacancy were identified as the two primary candidates forming the charge tail, the next step was to extrapolate the most likely trap defect landscapes from the Pyxel calibration results. To accomplish this, CDM simulations of the charge tails from the different fitted trap defects were compared against the charge tails produced from the C3TM simulations of the known radiation-induced trap defects. The densities of the C3TM simulations were varied to find the lowest goodness-of-fit $\chi^2$ value between the tails; this identifies the trap density that would best match the behaviour from the CDM simulations.

Figure 8.20 details a plot comparing a CDM charge tail against multiple charge tails produced from C3TM. Figure 8.20 also verifies that the combined effects of the trap de-
fects with emission time constants of the order of magnitude of $10^{-2}$s and $10^{-1}$s found from CDM replicate the behaviour of the “unknown” charge tail in C3TM reasonably well. The $\chi^2$ values between the CDM tail and the C3TM tails are 1.79 and 2.89 for C3TM “unknown” densities of $7 \times 10^9$ traps cm$^{-3}$ and $6.5 \times 10^9$ traps cm$^{-3}$ respectively. A point should be noted about the accuracy and reliability of the following results. The Pyxel calibration results used 5-6 sets of input and target files, each at different signal levels, so the Pyxel results should be reasonably reliable. For the comparisons with the C3TM charge tails, only one signal level was used to speed up processing time.

![Fig. 8.20](image.png)

**Fig. 8.20** A comparison of the CDM charge tail produced using the Pyxel-calibration results for the on-ground data against charge tails generated from C3TM with different trap densities. The charge tails are all following a charge block of 10,000 electrons.

While the divacancy and the “unknown” can easily be simulated and accounted for, the same cannot be said for the continuum. The continuum is produced in larger concentrations following cryogenic irradiations and the density of the continuum defects change depending on what kind of temperature anneal the device is experienced to. To obtain reasonable estimates for the Continuum, results from other studies are used as a comparison point (Buggey 2021).

For this analysis, the Pyxel charge tails were compared to charge tails from the divacancy and the “unknown” to find the best-fit trap density. After this, various densities
of continuum were added to the C3TM simulations to try and improve the best-fit $\chi^2$. It was found that higher densities of Continuum were required to best match with the results in the in-flight data. This tracks with previous results where cryogenic irradiations, which are more reflective of the space environment, produce a larger proportion of Continuum defects (Parsons et al. 2021).

### 8.6.4 Best-fit trap densities

Using the aforementioned steps, it becomes possible to obtain trap densities that would best model the charge calibration data. Figures 8.21-8.23 detail the best-fit comparison plots of the CDM and the C3TM charge tails with the $\chi^2$ values in the captions. Once the best-fit trap densities were found for each of the calibrated trap defects, C3TM simulations were made with all the three trap defects collectively. These simulations were then compared with the in-flight and on-ground charge tails produced using the Pyxel results in CDM and with the charge calibration data itself.

![Fig. 8.21 Charge tails from a CDM simulation of the fastest in-flight calibrated trap defect and a C3TM simulation with the best-fit trap densities; $\chi^2 = 0.39$. The charge tails trail a 12,370-electron signal in their respective simulation.](image)

The C3TM simulations that combine all the fitted trap defect densities are used to extrapolate the trap densities that are present in the on-ground and in-flight data. The charge tails of the new C3TM simulations are compared with the charge tails from the
Fig. 8.22  Charge tails from a CDM simulation of two of the in-flight calibrated trap defects and a C3TM simulation with the best-fit trap densities; $\chi^2 = 1.66$. The charge tails trail a 12,370-electron signal in their respective simulations.

Fig. 8.23  Charge tails from a CDM simulation of two of the on-ground calibrated trap defects and a C3TM simulation with the best-fit trap density; $\chi^2 = 1.58$. The charge tails trail a 10,000-electron signal in their respective simulations.

on-ground data and charge tails from the full CDM simulation of the in-flight data. The reason the C3TM charge tails were compared against the CDM simulation of the in-flight data initially, rather than the data itself, was because, as noted in 8.4.4, the CDM
results underestimate the amount of CTI.

Due to non-intuitive effects of trap capture and emission and how the CTI behaviour changes when different trap defects are present, the trap densities in the C3TM simulations of the three trap defects were adjusted to lower the $\chi^2$ between the charge tails. This explains why the trap densities that best match the individual Pyxel calibrated results are not the same as the collective trap densities that best match the data itself. The C3TM trap densities were adjusted until a set of results was found that gave the lowest $\chi^2$ value against the on-ground data ($\chi^2=4.96$) and the CDM simulation of the in-flight data ($\chi^2=2.85$). The charge tails from these results were then compared against the CDM simulation of the on-ground data and the in-flight data respectively. Figures 8.24 and 8.25 compare the charge tails from these best-fit C3TM trap densities against the charge tails from the respective CDM simulations and the on-ground and in-flight data respectively.

The trap defect densities that best match the Pyxel results are detailed in Table 8.5 for both the in-flight and the on-ground data. It is noted that the in-flight data is modelled with a larger trap density of continuum as compared to the on-ground data. The on-ground data by comparison has a larger proportion of divacancies and “unknown” defects, with the “unknown” dominating much more in the on-ground data. This infor-
Fig. 8.25 (a) Comparison of the charge tails from a 12,370-electron charge injection from the in-flight data and a C3TM simulation with the best-fit trap densities ($\chi^2 = 15.46$). (b) Comparison of the charge tails from a 10,000-electron charge injection from a CDM simulation using Pyxel’s best fit parameters for the in-flight data and a C3TM simulation with the best-fit trap densities ($\chi^2 = 2.85$).

While this information is currently the best-known data about the Gaia CCD’s trap defect landscapes. While this information is useful to get an idea for the relative trap densities, further analysis is performed to get an understanding about the individual CTI impact of the traps and how they can relate to the radiation dose and be used for other studies.

Table 8.5 C3TM trap defect densities where the charge tails in the simulations best match the charge tails of the on-ground data and the CDM simulation of the Pyxel-calibrated in-flight data.

<table>
<thead>
<tr>
<th>Trap Defects</th>
<th>On-ground modelled density (traps cm$^{-3}$)</th>
<th>In-flight modelled density (traps cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$VV^{--}$</td>
<td>$2.5 \times 10^{11}$</td>
<td>$5 \times 10^{10}$</td>
</tr>
<tr>
<td>Continuum</td>
<td>$5 \times 10^{8}$</td>
<td>$1.2 \times 10^{9}$</td>
</tr>
<tr>
<td>“Unknown”</td>
<td>$6.8 \times 10^{9}$</td>
<td>$9 \times 10^{8}$</td>
</tr>
</tbody>
</table>

While this procedure can produce trap density results that would best describe the data, there is still an element of uncertainty. This is due to the fact that there a number of simplifications and assumptions, as previously described, as well as due to the fact that this procedure measures the observed features of a collection of traps as opposed to an analysis procedure like trap-pumping where it is possible to obtain detailed measurements of each of the individual trap defects. Having said that, while these results may not be the exact answer, they are likely very close to the true answer given all the
analysis steps taken and can be used to infer trap defect properties.

### 8.6.5 Effective impact and charge loss

In order to gauge a better understanding of the physical effects of the trap defects and their subsequent densities, another analysis was performed. For each of the three different trap species, C3TM simulations of charge injections were made at the same signal level and trap density. A percentage charge loss was then calculated as the number of electrons lost from the first five pixels over the signal level. The charge loss from the first pixels was taken instead of the trailing pixels because the trailing pixel tails would extend several pixels and the aim was to keep the EPER analysis consistent with a 10-pixel tail throughout the study. The percentage charge loss values were then multiplied with the best-fit trap densities from Table 8.5 to get an idea of the effective charge loss values and the CTI impact of each trap species and subsequent density. The percentage and effective charge loss values are detailed in Table 8.6; the percentage charge loss values are with respect to the original simulated signal and are not supposed to collectively sum to 100%.

**Table 8.6** Percentage charge loss values for the same density \(1 \times 10^{10} \text{ traps cm}^{-3}\) of different trap defects for a 10,000-electron signal along with the “effective impact” of each trap defect for both on-ground and in-flight testing, calculated by multiplying the charge loss values with the best-fit trap densities from Table 8.5.

<table>
<thead>
<tr>
<th>Trap Defects</th>
<th>Charge Loss (%)</th>
<th>On-ground</th>
<th>In-flight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modelled density (traps cm(^{-3}))</td>
<td>Effective impact</td>
<td>Norm. effect. impact</td>
</tr>
<tr>
<td>VV(^{--})</td>
<td>0.02 (2.5 \times 10^{11})</td>
<td>5 (10^{9})</td>
<td>0.12</td>
</tr>
<tr>
<td>Continuum</td>
<td>10.03 (5 \times 10^{8})</td>
<td>5 (10^{9})</td>
<td>0.12</td>
</tr>
<tr>
<td>“Unknown”</td>
<td>4.67 (6.8 \times 10^{9})</td>
<td>3.2 (10^{10})</td>
<td>0.76</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>1.0</td>
</tr>
</tbody>
</table>

It is noted that the percentage charge loss value of the divacancy is substantially less than those of the other trap species; this is despite the higher trap densities compared to the other defects. This makes sense given the nature of the almost single pixel charge tail. It is noted that the percentage charge loss of the continuum is the highest which is reflective of the continuum defects’ emission time constants being located around the region of Gaia’s TDI speed. The higher density of continuum in the in-flight data...
means there is a larger CTI contribution from the continuum in-flight. Despite having a comparatively lower percentage charge loss, the larger density of the “Unknown” means that it has a much more substantial contribution on the on-ground CTI; almost double the contribution from the in-flight trap landscape. This illustrates how the difference in trap densities leads to differences in the CTI impact. Comparing the total effective charge loss values reveals that the in-flight trap landscape produces over two times less CTI as compared to the on-ground trap landscape.

8.7 Radiation dose analysis and quantification

From the modelled trap landscapes, insights have been gained about the trap defects present in the in-flight and on-ground CCDs. By comparing the trap densities in the on-ground CCDs to the trap densities of the in-flight CCDs, it becomes possible to quantify the difference in radiation dose received by the two different CCDs, independent of straylight impacts. This allows for an extrapolation of the radiation dose factor and returns the analysis to the objectives introduced in the beginning of the chapter. Quantifying the radiation dose factor through the modelled trap densities means that the impact of all sources of radiation in-flight, be that solar radiation or galactic cosmic rays, all get absorbed into this single factor.

Ideally, the trap densities of different trap defects could be compared between the on-ground and in-flight modelled trap landscapes and an average radiation dose difference can be obtained. However, as has been noted in previous studies, cryogenic irradiations lead to the formation of a continuum of defects and a smaller production of divacancies as compared to room-temperature irradiations. This phenomenon is highlighted in Figure 8.26, which details the difference in trap landscapes between a room-temperature and a cryogenic irradiation. The modelled trap densities with Gaia would suggest that similar trap defect production has occurred on the in-flight CCDs. This makes it difficult to disentangle how much of the divacancy and continuum trap densities are due to a different radiation dose and how much is due to the cryogenic in-flight conditions.

The impact of trap landscapes from cryogenic irradiations is analysed further with the help of C3TM simulations in Chapter 9. While the radiation dose cannot reliably be quantified from the modelled trap densities for the divacancies and the continuum,
An illustration of the difference in trap defect landscapes between a room-temperature and cryogenic-irradiated CCD. This illustration was made based on the CCD radiation damage studies of the Roman Space Telescope, SMILE and Euclid space missions (Lee-Payne et al. 2022, Parsons et al. 2021, Bush et al. 2016, Bush 2019).

From previous investigations, it has been noted that the trap density of the “unknown” is the same between a cryogenic and a room-temperature irradiation performed at the same dose (Bush 2019).

In a previous study that compared trap defects between a cryogenic and a room-temperature irradiated Gaia CCD, it was found that trap defects with a fitted emission time constant of 0.1s had the same density between the two irradiations. Given the results of this chapter, it is strongly suspected that this trap species was the “unknown” which leads more credence to the suggestion that the trap density of the “unknown” is the same in both irradiation conditions at the same dose (Hopkinson et al. 2009).

From these observations, it can be extrapolated that a comparison of the trap densities of the “unknown” between the on-ground and in-flight trap landscapes, allows for a comparison of the radiation dose between the on-ground and in-flight conditions, as well as a quantification of this radiation dose factor. From Table 8.5 and 8.6, it is noted that the modelled trap densities of the “unknown” in the on-ground CCDs...
(6.8 × 10⁹ traps cm⁻³) is almost an order of magnitude larger than the modelled trap densities in the in-flight CCDs (9 × 10⁸ traps cm⁻³). To be more precise, the density of the “unknown” is 7.56 times larger in the on-ground CCDs as compared to the in-flight ones. This suggests a larger radiation dose in the pre-flight irradiations by the same amount as compared to almost six years’ worth of in-flight irradiation. While a future investigation looking at the impact of different irradiation energies would be useful, for now, a radiation dose factor is obtained:

\[ f_{\text{dose}} = 7.56 \]  

### 8.8 Conclusions

Previous studies that have used CDM were focused on finding the best match with experimental data, with the primary objective of modelling the data (Short et al. 2013, Prod’homme 2011). Previous studies with C3TM have focused on replicating the experimental results of the Euclid CCDs (Skottfelt et al. 2017). The work in this chapter has used CDM and C3TM to extensively model both the in-flight and on-ground Gaia CTI data (from Chapters 6 and 7). This is the first time the two models have been used in conjunction and collectively, they’ve provided measurements for the in-flight and on-ground trap defect landscapes. The results have also revealed insights into the differences between the irradiations of the in-flight and on-ground devices. The in-flight data was modelled with lower densities of the “unknown” and divacancy but higher densities of the continuum as compared to the on-ground data.

This chapter has discussed the differences in radiation dose experienced between the in-flight and on-ground CCDs and the impact of the difference in dose on CTI effects. To quantitatively characterise the impact of radiation dose, a number of techniques were applied to the model the radiation-induced trap defect landscapes of the irradiated Gaia CCDs. This particular type of analysis has not to date been performed in this level of detail with the Gaia devices. This investigation has provided insight into the capabilities and limitations of different CTI simulation models.

One of the primary models used in this investigation was CDM, which was originally designed during the pre-flight testing stage of the Gaia mission. CDM was designed for fast-modelling of the data; even using Pyxel’s optimized calibration mode to
find the best-fit solutions, the solutions from CDM do not provide exact answers for the nature of the trap-defect landscape. However, meeting its original objectives, the results are able to very accurately the model the data which can be useful for some researchers depending on the context of the work. In order to obtain a deeper understanding of the trap landscapes, further analysis needs to be performed. Even though the CDM results are not physically realistic, they accurately replicate real, physical effects and can provide a starting point for other investigations.

Using the CDM results, comparisons were made using the physically more accurate C3TM simulation model utilising trap defect data from the literature. From this analysis, three defects were identified as being responsible for the bulk of the trailing charge CTI effects in the Gaia devices, as mentioned previously. These were the divacancy, the “unknown” and the continuum, the latter of which has only been identified in relatively more recent studies (Bush et al. 2021, Parsons et al. 2021). This modelling and comparison of the trap defect landscapes between the in-flight and on-ground data can also become a reference point for future investigations with other missions.

It has been noted that the in-flight CCDs, which have experienced irradiation in a cryogenic environment, are modelled with larger densities of the continuum as compared to the room-temperature irradiated, on-ground CCDs. The relative numbers of the continuum and divacancy between the in-flight and room-temperature irradiated CCDs seem to roughly agree with results from previous studies (Parsons et al. 2021). The relative impacts of the individual trap defects and trap densities were also quantified. It was found that the continuum causes the largest CTI contribution overall and seems responsible for most of the CTI measured in the in-flight devices. When comparing the in-flight and on-ground trap landscapes, the larger density of “unknown” in the on-ground devices produces larger CTI effects over the other defects. Comparing the difference in “unknown” trap densities allows for a quantification of the radiation dose.

When using C3TM, TCAD models of the Euclid CCDs were used instead of models of Gaia CCDs which means that while the results may not provide exact trap densities, they should provide relatively accurate ratios between the trap defects. Having understood the radiation dose impact in the context of Gaia, the conclusions from this analysis can be used in the radiation damage studies of other space missions.
CHAPTER 9

Cryogenic vs room-temperature irradiations

9.1 Introduction

As discussed in the previous chapter, cryogenic irradiations produce different trap defect landscapes, and by extension different CTI effects, as compared to room-temperature irradiations. This chapter will discuss the differences extensively as well as use C3TM simulations to try and quantify the cryogenic irradiation factor on Gaia data.

In past studies with silicon detectors, the temperature of irradiation has been known to have an impact on the formation and distribution of trap defects and the subsequent CTI performance. Despite this, the majority of irradiations for devices during pre-flight testing of different space missions were performed at room-temperature for practicality. However, with future space missions, the accuracy demands and sensitivity requirements from silicon based image sensors become more crucial and the use of cryogenic irradiations in pre-flight studies becomes more desirable to accurately measure and describe the CTI effects (Bush et al. 2016, Prod’homme et al. 2018).

A number of studies in the past have looked at the impact of not only cryogenic irradiations but subsequent room-temperature annealing. A study looking at the annealing behaviour of hot-pixel defects in the Hubble WFC-3 detectors found that there was a population of hot-pixel defects that annealed following a room-temperature anneal and there was a population that remained stable (Polidan et al. 2004). This behaviour has been demonstrated in another study with Swept Charge Devices (Gow et al. 2015). In addition to these studies, other cryogenic irradiation studies have been performed for other space missions such as for the Chandra X-ray observatory (Bautz et al. 2005) and multiple by Hopkinson on Gaia itself (Hopkinson et al. 2005, Hopkinson and Moham-
The broad conclusions from these studies are that cryogenic irradiations leads to the formation of a different trap-defect landscape as compared to room-temperature irradiations. The performance of the cryogenic irradiated devices was measured to change following a room-temperature anneal. This is theorised to be due to certain trap defects that were previously immobile at cryogenic temperatures becoming mobile at higher temperatures which leads to a change in dark signal and CTI behaviour. Comparatively more recent studies have revealed that cryogenic irradiations lead to the formation of a continuum of defects with a range of emission time constant values between the peak of divacancy defects and the “unknown” defects on a trap-landscape diagram. Temperature anneals have been noted to decrease the number of continuum traps while increasing the number of divacancy traps. Whether this is due to the continuum defects migrating directly into the peak of the divacancy is currently unknown but is something that could be investigated in the future (Skottfelt et al. 2018, Parsons et al. 2021).

Returning to the cryogenic irradiations performed on the Gaia devices by Hopkinson, the results found were very similar to the conclusions drawn from the more recent studies. Table 9.1 replicates Table 1 of the work from Hopkinson et al. (2009) and details the ratio between the densities of trap defects with fitted emission time constants from a cryogenic and a room-temperature irradiation. It is noted that the traps with the “fastest” emission time constants measure a lower density in the cryogenic irradiated data whereas traps with emission time constants between $1 \times 10^{-3}$s and 0.1s measure larger densities. Given the emission time constant and trap defect analysis from Chapter 8 as well as the results from other studies, it is strongly suspected that these results are representative of the lower density of divacancy and higher density of continuum from the cryogenic irradiations. The defect concentrations were noted to be different between the cryogenic and room-temperature irradiations by a factor of 3.5 and bringing the device to $100^\circ C$ was seen to further reduce the CTI by a factor of 1.5 (Hopkinson et al. 2009).

## 9.2 C3TM simulations

From this discussion, it is apparent that the in-flight cryogenic conditions would cause different CTI behaviour as compared to what was measured from the on-ground pre-
Table 9.1 The trap concentrations immediately after a cold irradiation relative to the trap concentration for a room-temperature irradiation with a 2-week room-temperature anneal. This table is a replication of Table 1 from Hopkinson et al. (2009).

<table>
<thead>
<tr>
<th>Emission time constant (s)</th>
<th>&lt; $1 \times 10^{-3}$</th>
<th>$3 \times 10^{-3}$</th>
<th>$1 \times 10^{-2}$</th>
<th>$3 \times 10^{-2}$</th>
<th>0.1</th>
<th>&gt; 0.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative trap concentration</td>
<td>0.85</td>
<td>3.5</td>
<td>2.2</td>
<td>1.5</td>
<td>1</td>
<td>0.75</td>
</tr>
</tbody>
</table>

flight tests. While the cryogenic studies at the time measured different trap defect landscapes as compared to room-temperature results, the factor was measured to be less than a factor of 2-3.5. Given that the room-temperature results seemed to give a good estimate of the effects of the traps, it was concluded that the room-temperature irradiations would have been adequate for Gaia’s performance predictions (Hopkinson et al. 2009). Given more recent results, it is now clear that even this factor of 2-3.5 is significant enough to be worth re-investigation.

Over its mission lifetime, the Gaia spacecraft has undergone a number of heating events to decontaminate ice that has accumulated on-board. There is a chance for these heating events to have caused annealing of the trap defects. However, given the temperature of the controlled heating events, the lack of overall change in CTI measurements following the heating events, as well as studies that have looked at annealing of trap defects, it is not believed that the Gaia focal plane reached a significant enough temperature for annealing to have taken place during these heating events (Crowley et al. 2016a,b, Parsons et al. 2021).

The results from Chapter 8 have shown that the in-flight charge data was modelled with different densities of divacancies and continuum as compared to the on-ground data. While some of this could be reflective of the difference between irradiation temperature, there is a contribution from the radiation dose that is non-intuitive to disentangle. In order to model and quantify the impact of cryogenic irradiations on the Gaia data, C3TM simulations are used once again. By making simulations of a cryogenic and a room-temperature trap landscape, the differences can be quantified and compared between the two.

To perform C3TM simulations, trap defect landscapes are required as an input. No detailed trap defect landscapes are present in the literature for the Gaia CCDs, so the trap
The results were used from radiation damage studies of the CCD201 device (Bush et al. 2021), which will be implemented on the Nancy Grace Roman Space Telescope, and the CCD273 device (Skottfelt et al. 2017, Lee-Payne et al. 2022), which will be used on the Euclid spacecraft. Although neither of these devices are the same as Gaia’s CCD91-72 device, the three devices are all n-channel silicon-based CCDs with similar structures and material components. While the exact trap defect landscapes will be different between the devices, the overall ratios between trap defects should be similar between the devices, as has been noted in other CCD radiation damage studies. While the C3TM simulations of the CCD201 and CCD273 trap landscapes may not be representative of the exact answer for Gaia’s CCD91-72, they should hopefully be very close to the true answer.

Table 9.2 details the simulated C3TM trap defect densities that were made to quantify the impact of cryogenic irradiations. The room-temperature trap densities are taken from the radiation damage studies of the CCD201 with the results scaled by a factor of 10 so the densities align with the modelled results from Chapter 8 (Bush et al. 2021). The cryogenic trap densities replicate the room-temperature trap densities for all the trap defects except for the continuum and the divacancy. The density of continuum and divacancy is extrapolated from studies comparing the trap densities of room temperature and cryogenic irradiated CCD273 devices (Lee-Payne et al. 2022). The densities are scaled from this study to match the results of Chapter 8 and the CCD201 results. This ratio between the continuum and divacancy is important as it is the primary reason for CTI differences between cryogenic and room temperature irradiations.

In Table 9.2, a concentration of slower trap defects are included to try and simulate charge capture and CTI effects in the Gaia devices as accurately as possible. The A-centre is not included as it is known to be too fast to produce any noticeable CTI results in the parallel transfer direction.

To compare the CTI effects between the room-temperature and cryogenic trap landscapes, a charge injection scheme is simulated in C3TM, as detailed in Figure 9.1. This charge injection scheme has a period of 2000 TDI, simulated to resemble the charge calibration data from the on-ground results of Chapter 7 as well as the in-flight charge injection scheme implemented on the AF CCDs. The C3TM simulations were also
Table 9.2 A comparison of the radiation-induced trap defect landscapes that were simulated with C3TM to represent a cryogenic and a room-temperature irradiation. The trap densities were extrapolated from the results of Bush et al. (2021) and Lee-Payne et al. (2022).

<table>
<thead>
<tr>
<th>Trap Defect</th>
<th>Room-temperature Irradiated densities (traps cm(^{-3}))</th>
<th>Cryogenic Irradiated densities (traps cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow-release traps</td>
<td>6.2 \times 10^9</td>
<td>6.2 \times 10^9</td>
</tr>
<tr>
<td>“Unknown”</td>
<td>5.3 \times 10^9</td>
<td>5.3 \times 10^9</td>
</tr>
<tr>
<td>VV ---</td>
<td>7.1 \times 10^{10}</td>
<td>2.8 \times 10^{10}</td>
</tr>
<tr>
<td>Continuum</td>
<td>1.3 \times 10^{10}</td>
<td>6.8 \times 10^{10}</td>
</tr>
</tbody>
</table>

made at a signal level of 450 electrons for a reliable comparison against the smallest signal level investigated in Chapter 7. Given that most of Gaia’s measurements are towards the fainter end, this signal level allows for an examination of the maximum possible CTI impact of a cryogenic irradiation.

As mentioned in Chapter 8, Gaia Silvaco pixel models could not be developed for these simulations, so the simulations are made using the Euclid pixel model, with the parameters adapted to match those of Gaia’s pixels. The Euclid charge models also do not contain an SBC so the CTI results for the 450-electron signal may be overestimated. As has already been stated, while an exact solution will not be feasible, a reasonable approximation should be obtained as a reference point. It is important to take this uncertainty into account when discussing the results and planning future research.

9.3 Quantification of cryogenic irradiations

With the CI scheme in Figure 9.1 and the trap densities from Table 9.2, C3TM simulations were generated at a signal level of 450 electrons. CTI calculations were then performed on the simulated results with the FPR and EPER measurement techniques. For FPR, the charge loss from the first pixel of charge was calculated with respect to the charge in the last pixel of the charge injection. For the EPER calculations, the sum of charge in the ten-pixel tail was calculated with respect to the signal in the last pixel of the charge injection. Table 9.3 details the CTI results.

From Table 9.3, it is noted that the cryogenic trap landscape measures a larger CTI compared to a room-temperature trap landscape, regardless of the measurement tech-
Fig. 9.1 The charge injection scheme simulated in C3TM for the two different trap landscapes detailed in Table 9.2.

Table 9.3 The CTI values for a signal level of 450-electrons for the charge injection scheme detailed in Figure 9.1, measured from the C3TM simulations of Table 9.2 using two different CTI measurement techniques.

<table>
<thead>
<tr>
<th>CTI Measurement</th>
<th>Cryogenic Irradiation</th>
<th>Room temperature Irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPR</td>
<td>$2.21 \times 10^{-4}$</td>
<td>$1.05 \times 10^{-4}$</td>
</tr>
<tr>
<td>EPER</td>
<td>$2.18 \times 10^{-4}$</td>
<td>$5.53 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

nique. This indicates that the continuum has a large impact on not only charge capture but also on the formation of the charge trail with respect to Gaia’s parameters. It
should be noted that these simulations were produced without an SBC; while the relative amount of charge trapping and charge loss should not vary considerably, there is a chance for these CTI results to be slightly overestimated.

The objective of making these measurements was to quantify a reasonable estimate for the impact of the in-flight cryogenic irradiations and how they compare to the room-temperature measurements. From the results of Table 9.3, the values in Table 9.4 are obtained which details the ratio between the CTI measurements between the two different irradiations. As noted, before, the CTI is higher for the cryogenic results with respect to the room-temperature results. It is interesting to note that this ratio is larger for the EPER measurements. This would suggest a substantial contribution to the charge tail from the continuum.

Table 9.4 The relationship between the CTI values for the two different irradiated trap landscapes for a 450-electron signal. These values quantify the impact of cryogenic irradiations on CTI measurements.

<table>
<thead>
<tr>
<th>CTI Measurement</th>
<th>CTI Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPR&lt;sub&gt;cryo&lt;/sub&gt; / FPR&lt;sub&gt;RT&lt;/sub&gt;</td>
<td>2.10</td>
</tr>
<tr>
<td>EPER&lt;sub&gt;cryo&lt;/sub&gt; / EPER&lt;sub&gt;RT&lt;/sub&gt;</td>
<td>3.94</td>
</tr>
</tbody>
</table>

When quantifying the cryogenic factor, the factor will decrease the overall CTI measured in-flight when compared to on-ground. For the cryogenic factor, the FPR ratio from Table 9.4 is used to provide the ideal comparison with the straylight factor results from Chapter 7; this returns a cryogenic factor of:

\[
f_{\text{cryogenic}} = 0.48
\]  

9.4 Conclusions

While previous studies have looked at the impacts of cryogenic irradiations, these studies have predominantly been experimental (Parsons et al. 2021, Bush et al. 2016). This chapter extends the analysis by simulating trap defects, using the results from the previous investigations, to study the CTI behaviour from cryogenic irradiations. This allows
for an alternate comparison between cryogenic and room-temperature irradiations by using C3TM simulations.

As has been noted in a number of different studies, cryogenic irradiations lead to a difference in the resulting trap-defect landscape as compared to room-temperature irradiations. Depending on the clocking speed of the CCD, a trap-defect landscape from a cryogenic irradiation can result in either a larger or smaller amount of CTI. In the case of Gaia, it has been noted that along the parallel TDI charge transfer timescales, a cryogenic irradiation produces a larger amount of CTI. In this chapter, C3TM simulations were produced to quantify the cryogenic factor and get a measurement for how much the CTI would differ as compared to a room-temperature irradiation. A number of approximations were made with the quantification of the cryogenic factor such as the use of CCD273 TCAD simulations and using scaled trap defect landscapes from results from irradiated CCD201s and CCD273s. Nevertheless, these results should be an accurate approximation of the true answer in the absence of physical trap-defect landscape measurements of irradiated Gaia CCDs. The cryogenic factor will be re-introduced and analysed with other factors in Chapter 10 of this thesis.
CHAPTER 10

Finalising results, conclusions and future work

10.1 Combining all the factors

From all the analysis performed in this thesis, it now becomes possible to combine the results together and solve equation 4.2 (re-introduced here as equation 10.1 below) to understand the discrepancies between the Gaia’s in-flight and on-ground CTI results. The in-flight CTI is smaller than the on-ground CTI by a factor of $\sim 7 - 8$. It is interesting to note this is approximately equivalent to the $f_{\text{dose}}$ factor ($f_{\text{dose}} = 7.56$ from equation 8.1). A simple analysis might therefore incorrectly conclude that the difference in radiation dose is the sole factor responsible for the on-ground/in-flight CTI discrepancy. However, it is now known from the results of this thesis that this is purely coincidental and that other factors impact the CTI in finite ways.

For equation 10.1, the values for $f_{\text{straylight}}$ can be extracted from Table 7.2, obtained from the analysis of on-ground CTI data detailed in Chapter 7. The $f_{\text{dose}}$ and $f_{\text{cryogenic}}$ factors are taken as 7.56 and 0.48 from equations 8.1 and 9.1 respectively; these were obtained from the radiation dose analysis of Chapter 8 and the cryogenic irradiation analysis of Chapter 9. For this calculation, $f_{\text{other}}$ is taken as one to see if the factors quantified in this thesis are sufficient to explain the disparity. All these factors are reproduced in Table 10.1.

Table 10.1 All the quantified factors affecting CTI, reproduced from the previous chapters.

<table>
<thead>
<tr>
<th>CTI Factors</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straylight (6.7e – pixel$^{-1}$)</td>
<td>1.45</td>
</tr>
<tr>
<td>Straylight (18.3e – pixel$^{-1}$)</td>
<td>1.6</td>
</tr>
<tr>
<td>Radiation Dose</td>
<td>7.56</td>
</tr>
<tr>
<td>Cryogenic Irradiation</td>
<td>0.48</td>
</tr>
</tbody>
</table>
\[ CTI_{ground} = CTI_{flight} \times f_{straylight} \times f_{cryogenic} \times f_{dose} \times f_{other} \] (10.1)

When combining the factors for a signal of 450 e− and using the in-flight representative background level of 6.7 e− pixel\(^{-1}\)s\(^{-1}\) for the straylight factor, a value of \(\sim 5.3\) is obtained which is lower than the \(\sim 7 \rightarrow 8\) factor. When using the straylight factor at the larger background level of 18.3 e− pixel\(^{-1}\)s\(^{-1}\), a value of \(\sim 5.8\) is obtained which is closer to but still not equal to the discrepancy between the in-flight and on-ground measurements.

If the cryogenic factor was higher, meaning the increase in CTI from cryogenic irradiations was lower, it could be feasible that the increase in CTI from cryogenic irradiations was being counter-balanced by the CTI mitigation from the in-flight straylight levels. This would mean that in the absence of straylight, the discrepancy between the in-flight and on-ground CTI would still be present but to a lesser degree. However, the results of this thesis indicate that there are other factors at play which means \(f_{other}\) cannot be assumed to be unity.

There are a number of different reasons, theorised in the previous chapters, which may have an impact on \(f_{other}\). These include:

- The in-flight incident particle energy spectrum - The in-flight CCDs are exposed to a wide-range of particle energies as opposed to the small, finite range used in the on-ground irradiations. This wide range of particle types and energies in-flight may cause a variation in the traps generated in the silicon compared to the on-ground testing. It has not yet been established if the population and distribution of traps produced in the silicon are the same between the multiple-energy spectrum and the single energy employed for on-ground irradiations, despite the fact that the non-ionizing energy loss in silicon is the same in both.

- Interactions of the radiation with the spacecraft - The incoming radiation could interact with parts of the spacecraft or the instruments in a way to change their energy and resulting fluence. Higher energy particles, which would have otherwise passed through the detectors, could lose their energy when passing through parts of the spacecraft. These, now lower energy, particles could now form trap defects
in the CCDs. There is also a chance for the emission of secondary particles when incoming radiation interacts with parts of the spacecraft but this was noted to be negligible in Gaia’s pre-flight simulations.

- Dosimetry difference - The in-flight CCDs receive a steady stream of radiation over a large period of time. By comparison, the on-ground CCDs were irradiated with a mission’s worth of radiation in a short time. It is likely that trap defects will form differently between a high-energy impact irradiation in a short period of time and a lower-energy irradiation over a long period of time. This in turn will lead to different CTI results between the two irradiation scenarios.

The aforementioned reasons are all possible contenders for the $f_{\text{other}}$ factor that should be investigated in future studies. Potential methods for doing so are discussed in the next section.

The results of this thesis have been able to more accurately quantify the discrepancy between the in-flight and on-ground results. While the radiation dose by itself matches this discrepancy, this is merely circumstantial and due to attributes specific to the Gaia spacecraft, such as the high straylight levels. The results of this thesis open up more avenues of investigation that can be explored in future radiation damage studies so that a greater understanding of CTI effects and mission performance can be realised.

**10.2 Thesis conclusions and future work**

**10.2.1 Quantifying $f_{\text{dose}}$ - Irradiation effects**

The results have shown that there is a finite contribution from $f_{\text{other}}$ in equation 10.1; this is likely to be due to the previously mentioned irradiation effects. A number of different investigations are proposed to study these effects and characterise $f_{\text{other}}$ with greater detail.

To investigate the impacts of the in-flight particle energy spectrum, it would be useful to perform irradiations at a range of energies. The CTI results and trap defect landscapes can then be studied in more detail to learn insights about the impacts of different irradiation energies. This will be useful when comparing in-flight and on-ground irradiations.
To study the interactions of radiation with instruments or spacecraft shielding in general, CCD irradiations should be performed with and without shielding. This can be achieved by placing a sheet of Aluminium or another suitable material in front of the CCDs during irradiation to mimic irradiation through instruments or different parts of a spacecraft. The CTI results and trap defect differences can again be studied to quantify the impact of shielding. This investigation can be linked with the particle energy investigations to establish any possible links between the particle energy and interaction of the particles with the materials. Detailed simulation modelling, such as with a software like Geant4, can also be performed to study this phenomenon.

The in-flight dosimetry is known to be different from that experienced during on-ground irradiations. This could be studied further through the use of specialised radiation campaigns. A recent example of this is from one of the SMILE radiation damage studies where a CCD was irradiated twice, with half the End-of-Mission (EoM) dose, at different intervals. The CTI was characterised after both sets of irradiations to track the impact of each dose and note any observed changes (Parsons et al. 2021). While it may not be logistically possible to replicate the irradiation dose over a mission lifetime, steps can be taken to obtain a reasonable approximation. Gaia was launched at the end of solar cycle 24 and is operating in the first half of solar cycle 25 as of the time of writing. A multi-phase irradiation scheme could be tailored in such a way to accurately assess the performance of in-flight devices over a unique radiation environment and timeline such as with Gaia.

10.2.2 Characterisation of different devices

A number of different results and insights have been revealed with respect to the characterisation of Gaia’s CCDs and their CTI measurements:

- The thicker RP device variants measured lower levels of initial serial CTI compared to the other device variants which all measured higher levels of initial serial CTI.

- The RP devices manufactured in 2009 were measured to have higher amounts of initial parallel CTI in comparison to RP devices that were manufactured before 2009 and all the other device variants.
• Across the focal plane, different CCDs measured different rates of CTI increase.
  – The BP and RP devices in particular measured larger rates of increase compared to the AF devices in contrast to their predicted NIEL dose.

• The trap defect landscapes of the in-flight and on-ground CCDs were characterised with a combination of the Pyxel framework and the CDM and C3TM models:
  – This is the highest level of characterisation performed on the Gaia devices as of the time of writing.
  – This was also the first comparison and joint-use of the CDM and C3TM models.
  – The faster CDM model could accurately replicate CTI effects in the Gaia charge calibration data but only achieved limited success when pushed beyond its objectives to accurately characterise the trap defects
  – While C3TM provides more physically accurate results compared to CDM, it is much slower to run. Using the CDM results as a starting point helped to cut down on computational time; this helped provide accurate trap defect results and also provides a framework for future investigations.
  – In the context of Gaia’s CCDs and operating parameters, the “unknown” trap and the continuum of traps were identified as the defects that would have the largest impact on CTI.

There was an attempt to measure the SBC FWCs of the in-flight RVS devices in Chapter 5 but this was unfortunately not possible with the initial data available. For future studies, a different set of data would be needed to achieve these objectives. This could be a charge injection scheme spanning several orders of magnitude or data acquired from an analysis technique such as trap-pumping.

To understand the differences in CTI behaviour between different CCDs, it would be useful to characterise similar CCDs with different thicknesses or variants. This in-depth characterisation should be performed on all, or as many of the in-flight devices as possible, to identify discrepancies between devices and performance. The study of the device variants can also be linked to the various irradiation studies that were proposed.
to understand the behaviour of different device variants as best as possible. Overall, the results of this thesis have identified that a number of different factors can affect the CTI measurements and device performance. Future investigations will need to study a number of different factors depending on the requirements for future space missions.

C3TM simulations have a large computational cost and the results of this thesis have shown that CDM simulations can be used as a starting point to save on computational time.

10.2.3 Cryogenic Irradiations

This thesis has revealed some insights into the nature of cryogenic irradiations on the Gaia devices.

- The results of Chapter 8 have revealed differences in the trap landscapes between the in-flight and on-ground CCDs which is a representation of the real effects of in-flight cryogenic conditions versus on-ground room-temperature irradiations.

- The results of Chapter 9 have revealed that cryogenic irradiations lead to higher CTI results with respect to Gaia’s operating conditions.

Performing cryogenic irradiations is a relatively new and developing research area with respect to silicon detectors. Future radiation damage studies should be performed at both cryogenic and room-temperatures to bound the radiation-induced CTI results. Using experimental results in conjunction with simulations would reveal more insights into the nature of radiation damage in space.

10.2.4 The Gaia mission

Bringing the results and conclusions back to the performance of the Gaia spacecraft:

- The in-flight CTI results have not shown any significant deviations in their behaviour in time.

- The parallel and serial CTI measured a steady near-constant increase in time, well-correlated with the solar activity.
• While the lower solar activity has been noted to be a major factor responsible for the discrepancy between the in-flight and on-ground CTI results, this thesis has revealed that the situation is more nuanced and several different factors are at play.

Gaia has been performing well since launch and has gone well beyond the nominal mission lifetime. At the time of the writing of this thesis, its latest mission extension has been granted until the end of 2025; it is only limited by its on-board propulsion fuel.

Most, if not all the factors affecting the performance of Gaia’s CCDs were circumstantial to Gaia itself (straylight levels, solar activity etc). The results of this thesis can provide different avenues of study for future space missions to accurately predict and prepare for different behaviours.
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