GAIA ASTROMETRIC CCDS AND FOCAL PLANE

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ABSTRACT

The astrometric focal plane will have an area of almost 0.5 m^2 and will contain 170 CCDs. These will be operated in TDI mode in order to track and observe stars from both telescope viewing directions simultaneously. Gaia's target for astrometric precision of a few millionths of an arc second, places extreme demands on the focal plane thermo-mechanical stability and electronic performance. The CCDs themselves are large area, back illuminated, full-frame, four phase devices. They require maximum efficiency for observing the majority of objects, yet must simultaneously be able to handle very bright objects that will regularly cross the field of view. Achieving the final astrometric precision will also require excellent noise performance and MTF. In addition to demanding state of the art performance from each CCD, they will need to be produced in large numbers which raises production and yield issues. When analyzing Gaia data it will be essential to fully understand CCD behaviour, including the expected performance degradation due to radiation damage. This will be addressed through comprehensive testing and the development of detailed CCD models.

Key words: Gaia; CCDs.

1. FOCAL PLANE DESIGN

The Gaia astrometric telescope focal plane has an area of almost 0.5 m^2. Due to practical limitations on the size of each CCD, this focal plane will be populated with 170 devices, each with an active area of 45 $\times$ 59 mm (Figure 1). In order to maximize the fill-factor (minimize dead area), the CCDs must be located close together. This requires a novel package design with the electrical connections (flex circuits) attached to the side of each package (Figure 2). The flex circuits will connect directly to 170 dedicated Proximity Electronics Modules (PEMs) located behind the focal plane. Each PEM (Figure 3) will house the clock waveform generator and front end video chain for a single CCD. To ensure synchronous operation, a common TDI clock signal will be supplied to all PEMs for waveform generation.

In order for Gaia to achieve the specified astrometric accuracy, high thermo-mechanical stability is required in the focal plane (especially over time-scales of a few hours). In order to achieve this, the CCD support structure will be machined from Silicon Carbide (SiC) and will be mechanically isolated from the electronics support structure. Thermal shields will be included between the CCD support structure and the electronics support structure and the flex circuits connecting the CCDs and PEMs are designed to have a very low thermal conductivity. An exploded view of the focal plane structure is shown in Figure 4.

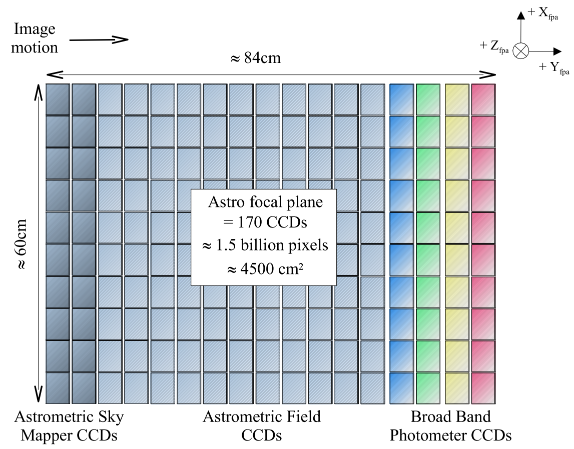

Figure 1. Schematic of the Gaia Astrometric focal plane.

2. CCD OPERATION IN TDI MODE

The Gaia satellite will spin continuously, causing the field of view of each telescope to scan across all objects located along great circles perpendicular to the spin axis. Data will be acquired continuously as the telescopes sweep out these great circles on the sky. For this reason the CCDs will operate in Time Delay and Integration (TDI) mode. This means that the CCD electrodes are clocked at the same speed as the image scans along the focal plane. In the astrometric focal plane, the image will cross 4500 pixels in 3.312 seconds. The integration time for each line transfer must therefore be 736 μs. Fur-

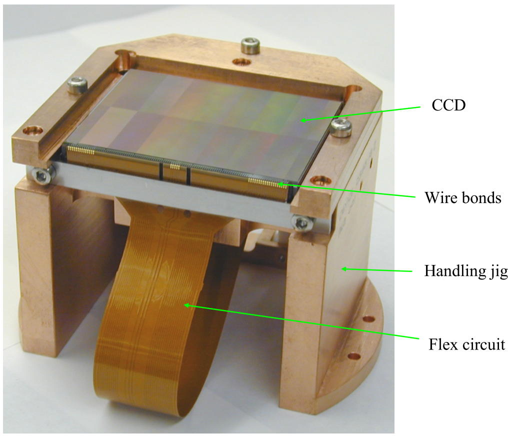

Figure 2. A prototype Gaia Astrometric CCD mounted in a copper handling jig. Note the flex circuit attached to the side of the package. Courtesy of e2v technologies.

thermore, the along scan dimensions of the four phases of a single astrometric CCD pixel are 2, 3, 2 and 3 μm respectively. The 736 μs period is therefore sub-divided between the four phases as 147.2, 220.8, 147.2 and 220.8 μs respectively to give the closest possible match between the motion of the incoming optical image and the motion of the integrating measured image.

3. CCD DESIGN

CCD detectors form the core of the Gaia payload. Their development and manufacture represents one of the key challenges for the programme, particularly in view of the large numbers required. Several CCD designs will be produced, tailored to the needs of the different instruments. We describe here, the CCD developed for use in the astrometric focal plane.

3.1. Architecture

In order to minimize the number required to fill the focal plane, the Gaia astrometric CCDs are very large area devices (approximately 26.5 cm^2). Their size is primarily dictated by the dimensions of a standard silicon wafer and by yield considerations (Figure 5). Like all Gaia CCDs, they are back illuminated, full-frame devices optimized for TDI operation at optical wavelengths. They have a 4-phase electrode structure in the image section, a parallel summing register and a 2-phase readout register leading to a single output node. Figure 6 indicates the dimensions and orientation of a single astrometric CCD. On-chip circuitry and bond pads are arranged in order to minimize the dead space around the image section.

Pixel size has been specified in order to properly sample the point spread function of the astrometric telescope whilst at the same time keeping the pixels as large as possible to maximize full-well capacity. This has resulted

Figure 3. A prototype Proximity Electronics Module (PEM). Courtesy of EADS Astrium and DLR.

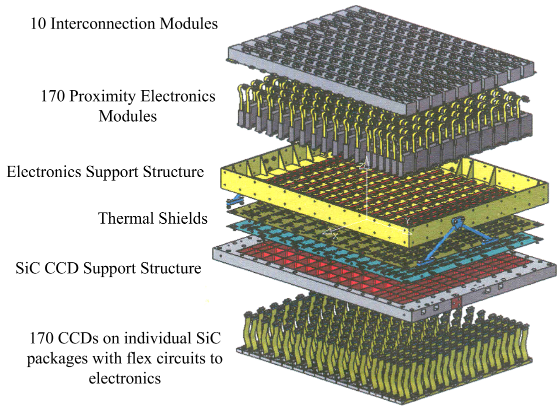

Figure 4. Exploded view of the Astrometric focal plane. Courtesy of EADS Astrium.

in dimensions of 10 μm in the along-scan direction and 30 μm in the across scan direction (Figure 7), giving a total of almost 9 million pixels per CCD.

3.2. Dynamic Range

Gaia will observe objects over a very wide range of apparent magnitude and the CCDs must therefore be capable of handling a wide dynamic signal range. In order to observe most (faint) objects as efficiently as possible, CCD QE must be maximized (Section 4.2) and CCD noise must be minimized (Section 4.5). At the same time, a number of features are incorporated into the CCD design in order to cope with bright sources. These include a large full-well capacity ($>$ 190 000 electrons), an anti-blooming drain and TDI gates which effectively reduce the integration time for very bright objects.

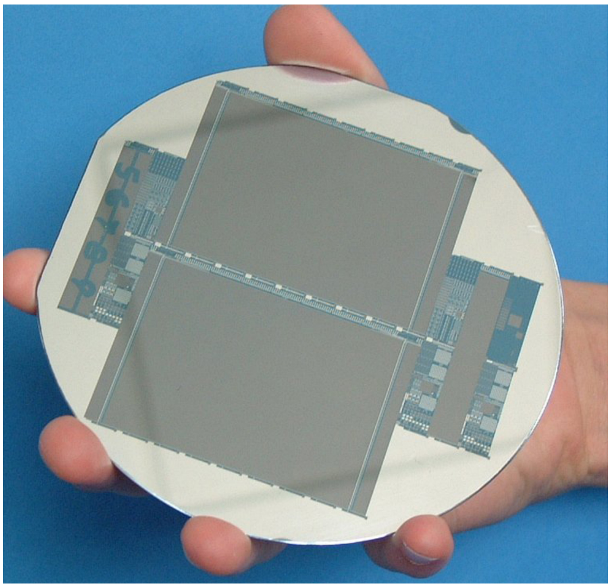

Figure 5. A Gaia silicon wafer. Two astrometric CCDs can be seen as well as a number of test structures. Courtesy of e2v technologies.

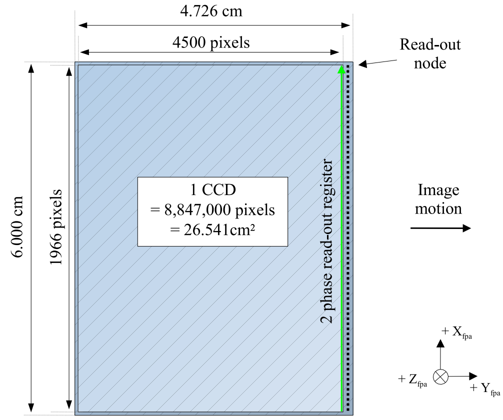

Figure 6. Schematic of a single Gaia astrometric CCD.

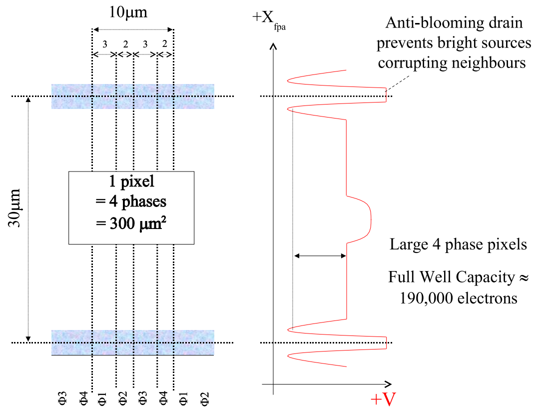

Figure 7. Schematic of a single Gaia astrometric CCD pixel (left) and representation of the across scan potential (right).

Figure 7 shows a single astrometric CCD pixel and a schematic representation of the across-scan potential under a biased electrode. The anti-blooming drains are located within the column isolation. When a bright source crosses the field of view, the number of electrons generated may exceed the pixel full-well capacity. In this case, excess electrons will flow over into the anti-blooming drain rather than into neighbouring pixels. Clearly the centre of the bright source PSF will be saturated, but the wings of the PSF and nearby sources will not be affected.

As an alternative to simply allowing bright sources to saturate (particularly when the bright source itself is of primary interest), TDI gates have been incorporated into the CCDs. Figure 8 indicates the locations of some of the TDI gates. These gates simply take the place of CCD electrodes and are normally clocked along with the electrodes so that they have no effect. However, any one of the TDI gates may be temporarily stopped in order to block the passage of a bright source. In this case, integration of the source (and any other sources parallel with it) begins again after the blocking TDI gate. In this way, the integration length (and hence time) can be reduced to 2400 lines, 2048 lines, 1024 lines and so on (to as few as 2 lines).

4. CCD PERFORMANCE

4.1. Depletion Depth

The depletion depth of a semiconductor device is simply the thickness of the depletion region, or that part of the material that has been depleted of majority carriers due to the presence of an electric potential. Since the depletion region is (by definition) that part of the device that supports the potential gradient (non-zero electric field), it is the part of a device capable of moving (or collecting) electrons quickly. Photon interactions within the depletion region liberate electrons which move quickly to the nearest potential maximum, usually within the CCD pixel in which they were liberated. Because response uniformity and production yield are important, we are constrained to using standard resistivity silicon for the Gaia astrometric CCDs. For this material, assuming typical CCD clock voltages, we can expect a mean depletion depth of $9 \pm 1\mu$m.

The remaining, undepleted thickness of a CCD is referred to as the field-free region. Electrons liberated by photons incident in the field-free region are also collected. However, in the absence of a strong electric field, they are able to spread laterally due to diffusion. This degrades the spatial resolving power of the CCD or Modulation Transfer Function (Section 4.3).

Figure 9 is a schematic representation of charge spreading in the depletion and field-free regions. t is the total

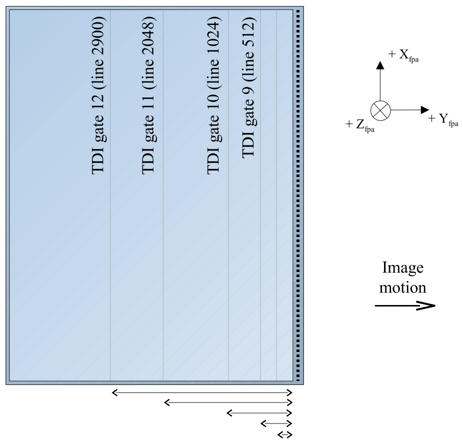

Figure 8. Schematic indicating the locations of the last 4 TDI gates. The 12 TDI gates are located at lines 2,4,8,16,32,64,128,256,512,1024,2048 and 2900.

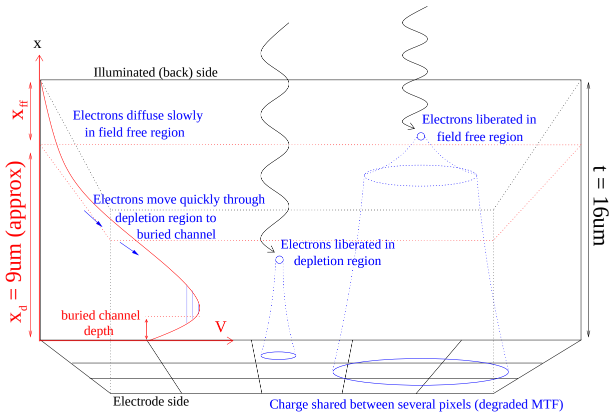

Figure 9. Schematic representation of charge spreading in the depletion and field-free regions.

thickness, x_d is the depletion depth and $x_{\rm ff}$ is the field-free thickness.

4.2. Quantum Efficiency (QE)

The Quantum Efficiency of a detector is simply the number of photons detected divided by the number of incident photons. In the optical wave-band, long wavelength (red) photons have a greater range in silicon than shorter wavelength (blue) photons. The efficiency of a detector in the red is therefore determined primarily by the thickness of the detector, whilst the efficiency in the blue is dictated primarily by surface reflection and hence the choice of anti-reflection coating. QE is also affected by internal reflections and by thin dead layers at both the front and rear of a CCD (which can vary in thickness and uniformity according to the passivation process implemented).

4.3. Modulation Transfer Function (MTF)

Modulation Transfer Function is the ability of a CCD to reproduce the contrast present in an image at a given spatial frequency. It is the product of three components, integration MTF, charge transfer MTF and charge diffusion MTF.

Integration MTF is the fundamental component due to the fact that a CCD samples a continuously varying image with an array of finite pixel elements. It defines an upper limit for the total MTF of 63% at the Nyquist spatial frequency. At longer wavelengths, Integration MTF is degraded by internal reflection which must be included in MTF models.

Charge transfer MTF describes the reduction in total MTF due to charge smearing during readout. It is significant for very large CCDs and/or when Charge Transfer Efficiency (CTE) is significantly degraded due to radiation damage.

Diffusion MTF is the component due to charge diffusion or spreading in the field-free region. Photon interactions liberate electrons with a density profile dictated by the PSF. The resulting clouds of electrons expand due to diffusion. The degree of spreading depends upon the collection time, the field strength and hence the interaction depth of the incident photons. Charge liberated in the field free region may be shared between two, several or many adjacent pixels, rather than being confined to the pixel in which it was liberated.

4.4. Optical Performance of the Baseline CCDs

In specifying the Gaia CCDs, one of the key issues is how much un-depleted material should be left during the back-thinning process in order to improve red QE at the expense of blue MTF. Simulations of Gaia astrometric accuracy have been conducted using theoretical QE and MTF curves over a range of *device total thickness* values. The optimum value is close to 12μm. However, it is not possible to thin such large devices to 12μm and the total thickness of the Gaia prototype astrometric CCDs is therefore the minimum practical (16μm).

In summary, the CCDs have been tuned for optical performance in the Gaia wave-band as follows: To be fabricated on standard resistivity material and back-thinned to a nominal thickness of 16μm. The nominal depletion depth for this material with typical surface voltages is approximately 9μm, leaving a field-free thickness of 7μm. The surface passivation will be the 'basic' e2v process in order to maximize yield. The anti-reflection coating will be a single layer of Hafnium oxide centered on 650 nm. This is a low risk design which is hoped will give a high yield of devices suitable for Gaia. The QE and MTF of the baseline astrometric CCDs are shown in Figures 10 and 11 respectively. These curves have been generated using models and are consistent with the first measurements conducted on prototype devices.

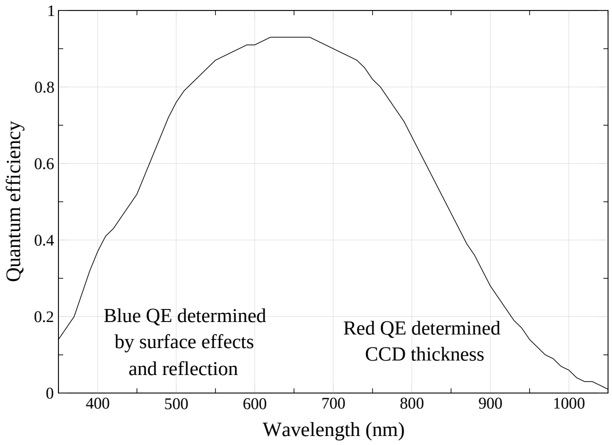

Figure 10. Quantum Efficiency (QE) of the baseline Gaia astrometric CCDs.

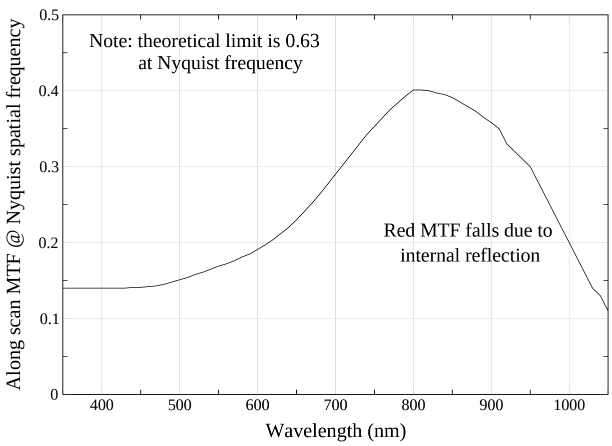

Figure 11. Modulation Transfer Function (MTF) of the baseline Gaia astrometric CCDs.

4.5. Noise

The CCD output node is a high performance two stage (buffered) design. At typical Gaia frequencies, the CCD is quite capable of noise performance better than 5 electrons RMS. This performance is expected to be degraded by the electronics bandwidth and increased capacitance due to inverted mounting (for back illumination). However, values better than 10 electrons RMS are still expected.

5. RADIATION EFFECTS

When operating detectors in space, one of the most important considerations is always the energetic particle radiation environment. At L2, this is essentially an interplanetary environment dominated by solar flare protons. Due to the size of the astrometric focal plane, it is only possible to incorporate minimal shielding for this instrument. Whilst this will be sufficient to reduce the ionizing radiation dose to less than 10 krad, the non-ionising (displacement damage) dose is expected to be high ($\sim 10^{10}$ protons 10 MeV equivalence). Radiation damage to the CCDs will degrade their performance and hence the overall performance of Gaia. In addition, particle events will potentially constitute a source of contamination and wasted telemetry in Gaia data.

5.1. Radiation Environment

There are two main sources of particles relevant to Gaia at L2:

- *Galactic Cosmic Rays (GCR)*: Very high energy particles (typically hundreds of MeV) which are mainly generated by supernovae. The rate observed varies from about 4 to 8 particles per cm^2 per second depending upon the phase of the solar cycle and they comprise approximately 90% protons, 9% He ions and 1% heavier ions. It is not possible to shield against Galactic Cosmic Rays effectively because their energy is high enough to penetrate many cm of shielding.
- *Solar particles*: Particles ejected directly from the Sun. The solar particle flux varies from essentially zero during solar quiet times to thousands of particles per cm^2 per second during periods of high solar activity. Like Galactic Cosmic Rays, solar particles are predominantly protons and helium ions. However, the peak energy of the solar proton spectrum is several orders of magnitude lower than that of the Galactic Cosmic Ray spectrum, so that shielding can be effective in reducing the dose to sensitive components.

5.2. Radiation Damage Mechanisms in CCDs

Nearly all damage to Gaia CCDs will occur during solar flares when the solar particle flux is thousands per cm^2 per second. As any particle passes through a CCD it causes two kinds of damage:

- *Ionizing damage*: In passing through the insulating layers of the electrode structure, a particle ionizes atoms. Over the course of a mission this leads to static charging of the electrode insulators which means that CCD operating voltages effectively drift with time. Ionizing radiation tests will be conducted on Gaia prototype CCDs to establish how susceptible they are, but it is currently estimated that voltages will drift by less than half a volt over 5 years.
- *Non-Ionizing or displacement damage*: As a particle passes through a CCD, there is a chance that it will collide with a silicon atom so as to displace it from its location in the crystal lattice, generating a point defect. Such defects introduce energy levels into the semiconductor bandgap into which electrons from the conduction band can drop and become trapped. Thanks to its thermal energy, a trapped electron may

jump back up into the conduction band (out of the trap), but this process has an associated de-trapping time constant which is a strong function of temperature. During the course of the mission, the high fluxes of solar protons during solar flares will generate a significant density of traps in the CCDs. The resultant trapping will lead to gradually worsening charge loss, smearing of the PSF and hence a reduction in centroiding (astrometric) accuracy.

5.3. Reducing the Effects of Radiation Damage in CCDs

Because trapping and especially de-trapping time constants are strong functions of temperature, one of the key methods for minimizing the effects of radiation damage is simply to select an optimum operating temperature. Operating warmer will cause electrons to escape from traps more quickly. However, it is not possible to operate too warm because this increases dark current and degrades the noise performance. Operating colder causes electrons to remain trapped for longer. This can be an advantage, because once a trap contains an electron it cannot trap another and is therefore rendered inactive. Unfortunately, radiation damage generates trap complexes with numerous energy levels and de-trapping time constants. Coupled with a dependence on CCD size and the transfer speed for a given application, this makes the selection of an optimum operating temperature rather complicated. Furthermore, it may be better to operate colder and accept a degree of charge loss in order to avoid operating in a regime in which deferred (or trailing) charge increases PSF distortion. The operating temperature for Gaia CCDs is currently expected to be about −115°C. This will be confirmed following radiation damage testing.

Several design features have also been incorporated into the Gaia CCDs in order to address radiation damage. A supplementary buried channel is included in the image section pixels (Figure 12). For relatively small signals, this causes the electrons to be transported through the CCD in a narrow stream so that they encounter fewer empty traps.

The CCDs also have a charge injection structure which may be used to periodically fill traps (Figure 13). Fast traps will quickly empty and become active again. However, traps with emission time constants longer than a few seconds may be effectively eliminated. The optimum frequency for charge injection will depend upon the CCD temperature. The effect of repeated charge injection on data analysis in terms of dead time and non-uniformity will need to be addressed. As an alternative to periodic charge injection, the structure may be used to inject a continuous, low level charge. Sometimes called a 'fat-zero', a similar technique has already been demonstrated on Hubble CCDs.

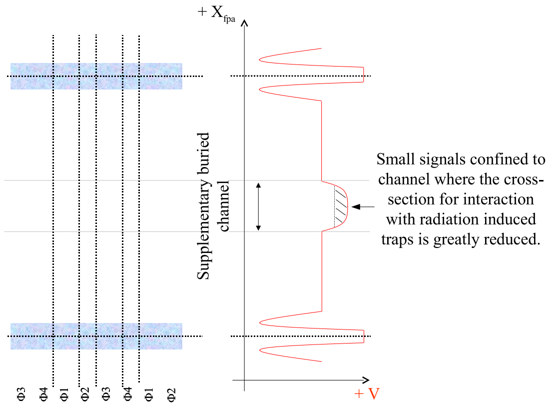

Figure 12. Schematic of an astrometric CCD pixel and across-scan potential indicating the supplementary buried channel.

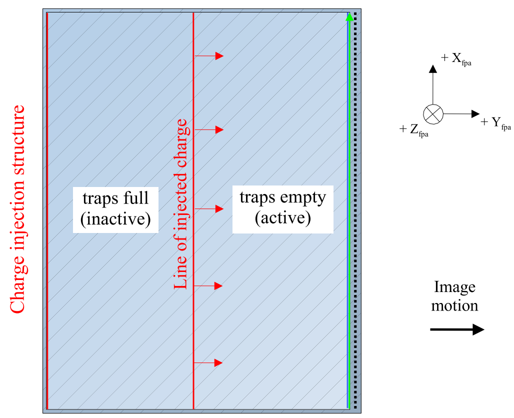

Figure 13. Schematic of an astrometric CCD indicating the location of the charge injection structure.

5.4. Particle Events in Gaia Data

During solar-quiet (observing) periods, there will always be a particle flux of between 4 and 8 Galactic Cosmic Rays per cm^2 per second passing through the Gaia CCDs. These background particle events will affect Gaia astrometric observations in several ways:

Astronomical sources are detected autonomously by the Astrometric Star Mappers (ASM). Particle events which are incorrectly identified as sources, will be assigned windows, tracked across the focal plane and transmitted to the ground. This is clearly a waste of resources and a reliable on-board rejection algorithm is required.

In addition, particle events close to sources in the astrometric CCDs, will introduce PSF distortion and hence centroiding errors. These errors need to be quantified and mitigation techniques assessed (such as the use of PSF matched filters in the centroiding algorithm). Once identified, a PSF contaminated by a particle detection may be corrected or rejected.

In order to begin addressing these issues, cosmic ray events are already being simulated using the monte-carlo CCD model described in Section 6.

6. CCD MODELLING AND SIMULATION

In support of the Gaia project, a number of simulation activities are being pursued by members of the Simulation Working Group and the Project Science Team. Among these are monte-carlo models developed by Brunel University and ESTEC which address the detailed behaviour of the CCDs. These tools will be applied to assessing the centroiding accuracy of the instruments in TDI mode, the impact of particle background events on centroiding accuracy and the effects of degradation due to radiation damage during the course of the mission. Sufficiently detailed models will enable predictions of Gaia performance and capability on the basis of CCD performance parameters and characteristics, which may be measured in the laboratory. They may also serve as tools for generating large quantities of simulated data with which to exercise the Gaia data processing chain.

In order to address the effects of radiation damage, the models must implement a dynamic treatment of electron trapping and de-trapping, charge injection, beneficial charge packets and so on. Modelling CCDs like this in a meaningful way is rather challenging. The concept under development at ESTEC comprises two arrays 4500 pixels long by 24 pixels wide. The first array represents the immobile CCD, containing traps and trapped electrons. The second array represents the 'conveyor-belt' of mobile electron packets. Each model cycle corresponds to a CCD line transfer (736 μs). During this period, the model carries out three steps:

1. Generate mobile electrons due to signal (e.g., PSF photons) and noise (e.g., protons, stray light). This encompasses not only the interactions of photons and particles within the CCD, but also the spreading of resultant electron clouds (due to diffusion) and mapping to pixels.
2. Transfer electrons between the mobile and trapped arrays according to trap occupancy, time constants etc. This is sub-divided into four steps corresponding to the four electrode phases of the CCD.
3. Translate the mobile charge by one pixel along scan and read out one serial register with appropriate binning, noise etc.

Figure 14 gives two examples of model output, with and without charge trapping and noise. The trapping parameters in this case are chosen to clearly illustrate the effects of trapping on a PSF in TDI mode. The first data from Gaia CCD radiation testing are now becoming available. These data will be used to test and verify the CCD models and to establish time constants and densities for the dominant trap species.

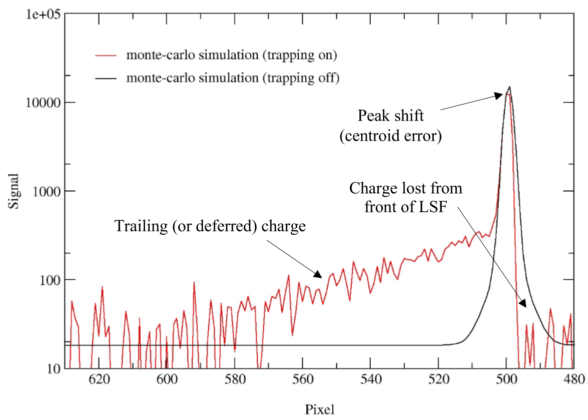

Figure 14. An example of monte-carlo model output indicating the effects of charge trapping on PSF shape.

7. DEVELOPMENT STATUS AND CONCLUSIONS

Many areas of the Gaia mission are technically challenging. For this reason, ESA is conducting a technology demonstrator phase and one of the key activities during this phase is the production of Astro focal plane Thermo-Mechanical and Electro-Optical Demonstrator Models. The activity is lead by EADS Astrium (Toulouse) with sub-contracts to e2v technologies (CCDs), DLR (PEMs), Sira Electro-Optics (radiation testing) and Leicester/Brunel Universities (analysis and modelling).

By the spring of 2004, Detailed Design Reviews were successfully completed for all demonstrator hardware. As of November 2004, hardware production is well advanced. The first batches of astrometric CCDs have been produced by e2v, tested (Figure 15) and delivered to Sira and Astrium. Structural components and thermal shields for both Demonstrator Models are complete (Figure 16) and ready to receive both the CCDs and the PEMs which are becoming available from DLR (Figure 3). CCD radiation testing is underway at Sira Electro-Optics and monte-carlo CCD models have been produced at Leicester/Brunel in preparation for fitting the radiation test data.

To-date, the aims of the study phase have been successful. The feasibility of producing large area Gaia CCDs and PEMs with the specified performance has been demonstrated. In the coming months a number of these units will be integrated into the Demonstrator Models and a period of Thermo-Mechanical and Electro-Optical testing will commence. In parallel, CCD radiation testing, analysis and interpretation will continue in order to establish whether or not Gaia can meet its astrometric accuracy targets in spite of the high radiation dose predicted. This is certainly one of the most critical issues facing Gaia at present.

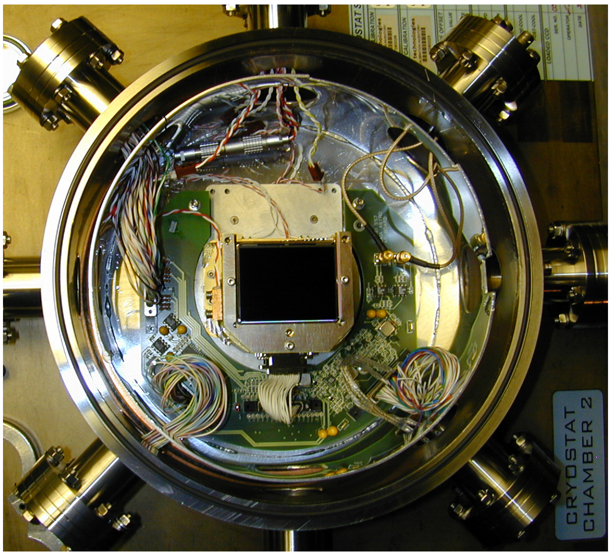

Figure 15. A prototype Gaia astrometric CCD mounted in a test facility vacuum chamber. Courtesy of e2v technologies.

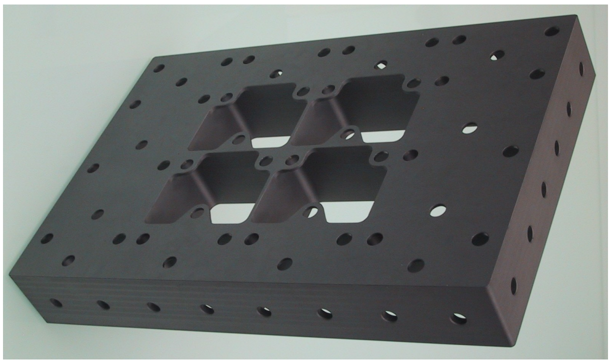

Figure 16. The Silicon Carbide (SiC) CCD support structure for the Electro-Optical Demonstrator Model. Courtesy of EADS Astrium.

ACKNOWLEDGMENTS

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