Gaia: electronic cameras in deep space

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At the heart of Gaia is an imaging system that employs charge-coupled devices (CCDs) consisting of arrays of optical light-sensitive elements. These CCDs are specially designed versions of the same kind of detector commonly found in digital cameras, but they operate in a particular mode and within the harsh environment of deep space. This results in anomalies in the measured signals, and the Edinburgh team is tasked with dealing with several aspects of this problem, along with associated calibration issues.

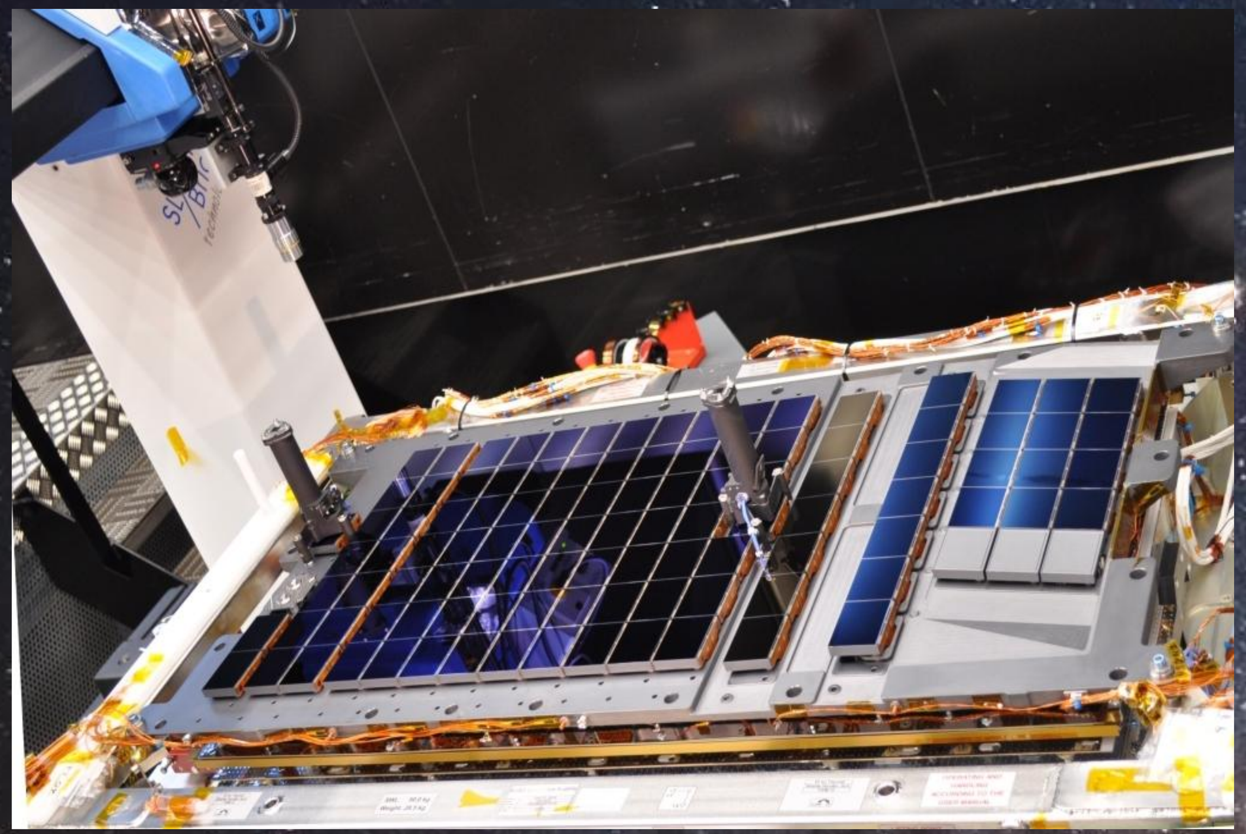


Figure 1: Gaia Focal Plane Assembly with all 106 Charge-Coupled Devices in place prior to integration into the science payload module. Picture credit: ESA / Airbus DS (formerly Astrium), October 2011.

One problem concerns the way the CCDs "see" the star field being scanned. In a domestic digital camera, we point at the scene of interest and then click the shutter to get an exposure of usually some fraction of a second. The CCD is then very quickly read out to capture an image of the scene as a stream of data numbers that reflect the electronic charge in each pixel produced by incident light from the scene. A clue to the way in which a CCD is read out is in the name: each pixel is "charge-coupled" to its neighbours such that once exposed, the array of charge measurements can be moved across the pixel array and into a line of light-insensitive, but similarly charge-coupled pixels. This line, known as the read-out register, is itself clocked to shift charge to produce a sequence of data numbers. Hence the CCD is read by shuffling each line of pixels in turn into this serial register. However in Gaia, rather than using the familiar point-and-shoot mode we commonly employ when using a digital camera, the CCD is continually clocked in what is known as time-delay integration (TDI) mode. As the satellite scans the sky, the CCD is continually clocked such that the scene shuffles across the device at a rate that exactly counteracts the scan. Hence, rather than observing individual pointed frames, a long image strip is imaged by each CCD. A (very) short simulated example of such a strip image is shown in Figure 2.

The simulation in Figure 2 shows several interesting features of Gaia imaging. For orientation, Gaia is scanning from right to left, while the CCDs are clocked to shuffle charge from left to right in order to compensate for the image motion. Ignoring the vertical stripes for the moment, we can see star images on a flat background with the familiar diffraction spikes introduced by Gaia's imaging system of mirrors. However if we look closely on the left hand (trailing) side of each image we can see that charge has been smeared away from the centre. This effect is known as charge-transfer inefficiency (CTI) and is the result of radiation damage to the CCD pixels. Incident radiation (primarily solar protons in this case) damage the crystalline structure of the CCD pixels inducing traps that grab charge from passing signals as they are shuffled along the columns of pixels. This trapped charge is then released a short time later, but after the signal has passed. In this way, the image of each star is distorted a small but significant amount, and this distortion will get worse as the radiation dose received by Gaia increases throughout its mission. Note that the bright vertical lines in the images are periodic, artificial "charge injections" that are employed in the Gaia CCDs to fill up charge traps as much as possible so that passing images are distorted less; the dark vertical lines correspond to transient reduced exposure times triggered by the transit of very bright stars to avoid CCD pixels becoming unusably soaked with charge in those images. While primarily beneficial, these phenomena create additional complications in the processing of Gaia data.

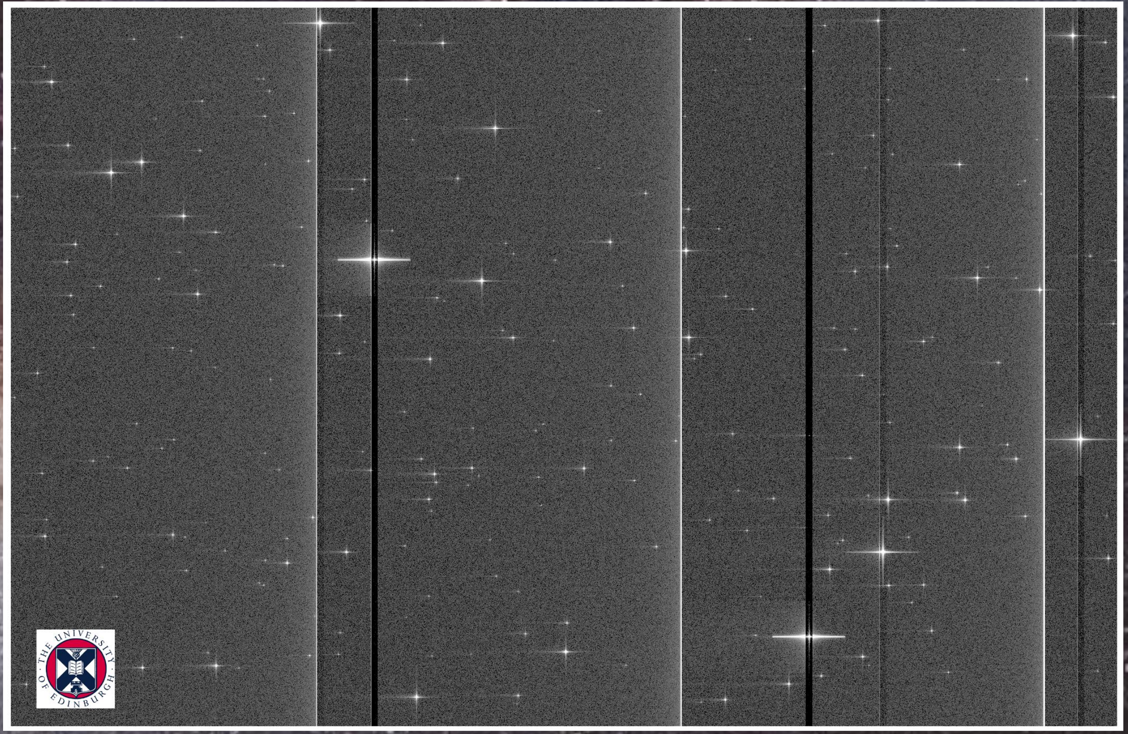


Figure 2: simulated image of the sky as seen by Gaia. Large-scale vertical and horizontal stripes are electronic instrumental effects resulting from the operating mode of the CCDs. The Edinburgh University team is responsible for monitoring, analysing and removing these effects in the Gaia data. This key step must be done before the astronomical information can be extracted from the image data. Picture credit: Edinburgh University IfA / "VitrualScan" Gaia simulator

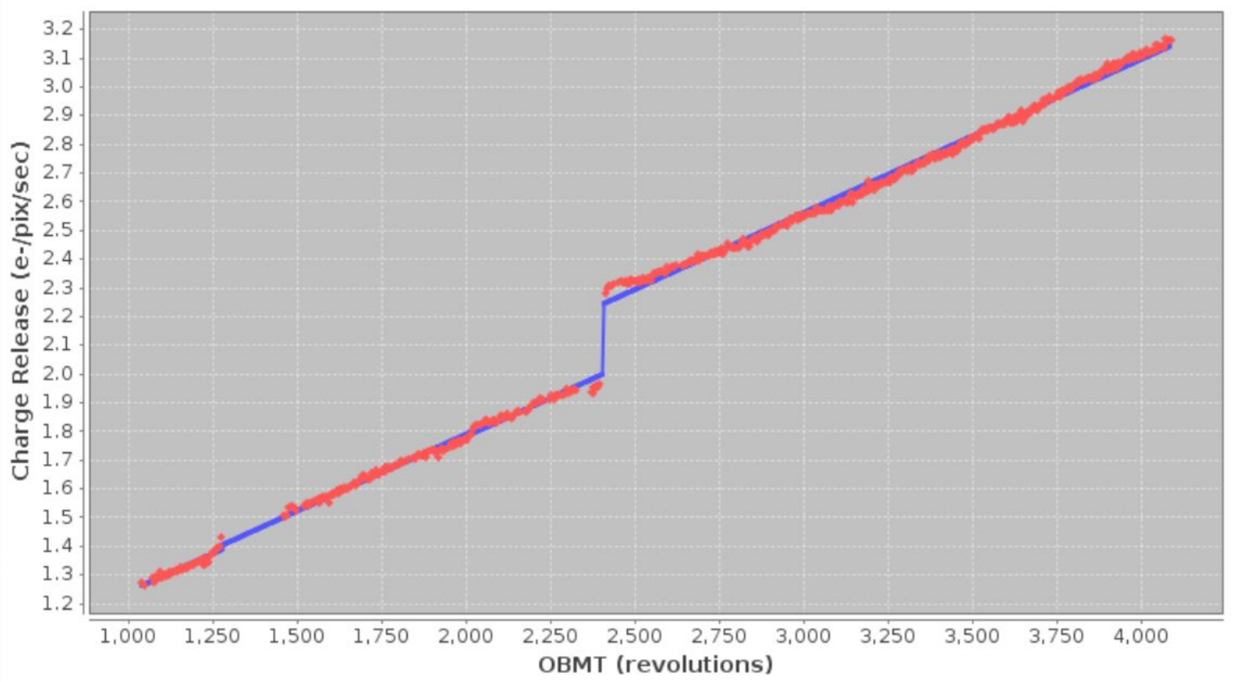
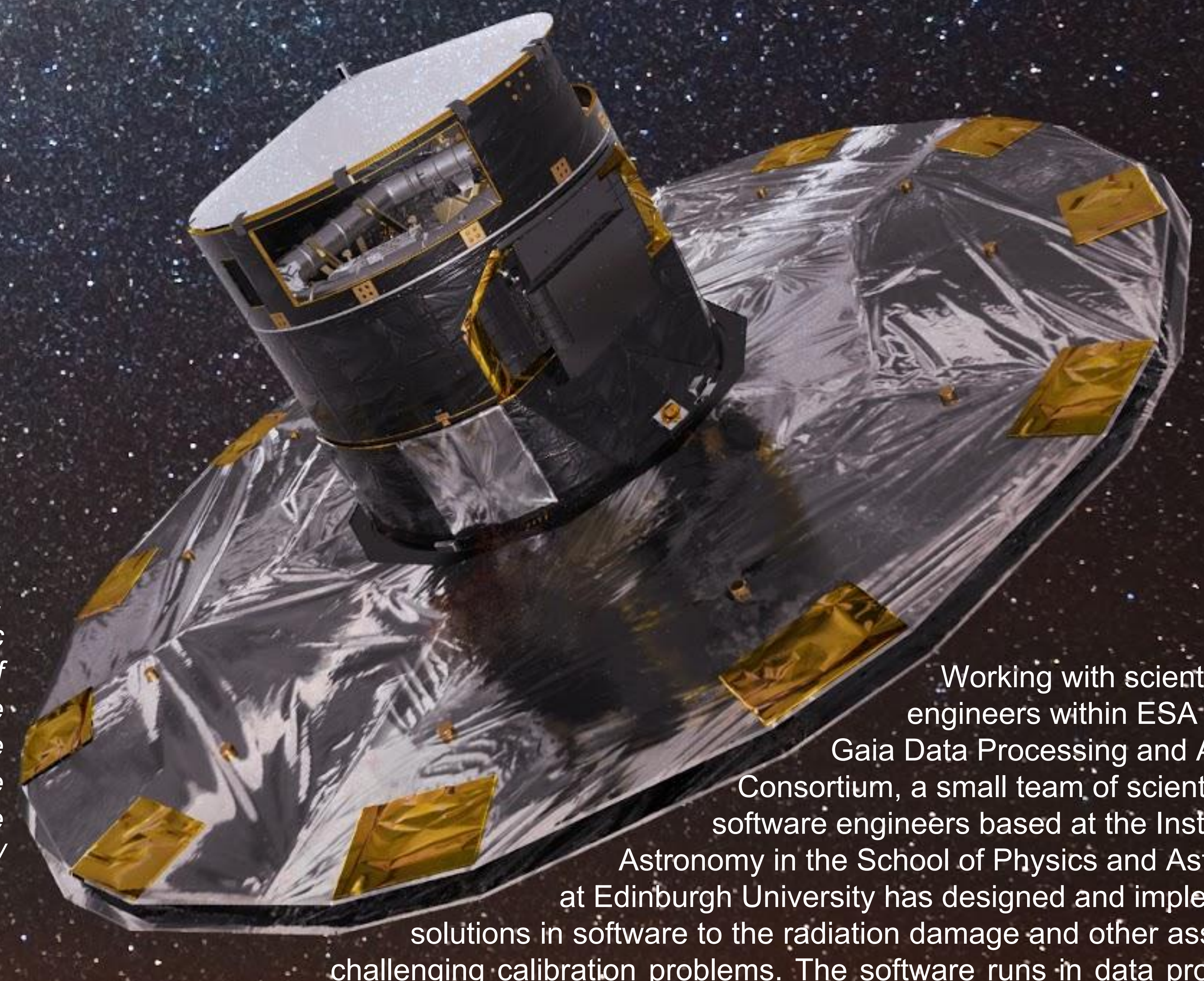


Figure 3: Evolution of radiation damage in Gaia's CCDs since launch, Red points show data from the satellite while the blue line is a simple model fit to the data. The horizontal axis has units of "On-Board Mission Time" revolutions of Gaia (1 revolution = 6 hours). A particularly severe solar storm took place near revolution 2,400 (which corresponds to mid-June 2015) and has resulted in a step increase in damage as measured in the charge released following the artificial charge injections. Picture credit: Edinburgh University IfA / "Sentinel" autonomous monitoring system



Working with scientists and engineers within ESA and the Gaia Data Processing and Analysis Consortium, a small team of scientists and software engineers based at the Institute for Astronomy in the School of Physics and Astronomy at Edinburgh University has designed and implemented solutions in software to the radiation damage and other associated challenging calibration problems. The software runs in data processing pipelines operating at various Gaia Data Processing Centres across Europe including those at Cambridge, Madrid, Barcelona and Paris.

Gaia Artist's impression - credits: ESA/ATG medialab; background image: ESO/S. Brunier