The Gaia Challenge: Testing High Performance CCDs in large quantities

Andrew Walker[a], Tim Eaton[a], Roy Steward[a], John Turton[a], Anthony Knoepfle[a], Tom Wynne[a], Peter Gillespie[a], Alastair Curnock[a], David Cooper[a], Arwel Evans[a], Matt Watcham[a]

[a] e2v technologies, 106 Waterhouse Lane, Chelmsford, Essex, CM1 2QU, England

ABSTRACT

Gaia, funded by ESA with EADS Astrium as the prime contractor, is an ambitious space observatory designed to measure the positions of around one billion stars with unprecedented accuracy and is currently planned for launch in 2011. The Gaia instrument will feature a focal plane containing 106 large area CCD91-72s manufactured by e2v technologies. This will be the largest CCD focal plane ever flown in space covering an area of $0.286m^2$. To ensure that the devices meet the required high specification, they undergo significant testing before being accepted by the end user. This involves geometrical, mechanical, environmental, endurance, electrical and electro-optical testing. With the flight phase contract for Gaia requiring the delivery of 130 flight grade devices (plus another 40 engineering devices of various grades), the volume of testing is an order of magnitude greater than and of similar timescale to, the typical space programmes e2v technologies are involved with. This paper will begin by providing an overview of the Gaia mission and the custom CCD91-72 that e2v technologies have designed for it. Next the various phases of the Gaia programme will be outlined and how e2v approached the test requirements for each stage. Problems encountered, lessons learned, and technical and logistical solutions implemented at each stage will be presented, to discuss how e2v technologies improved the quality of the test data whilst reducing the test times. There will be particular emphasis on the electro-optical testing and the test cameras on which this is performed.

Keywords: Gaia, CCD, CCD Test, Large area CCD, Buttable CCD, Focal Plane, Quantum Efficiency Measurement, Modulation Transfer Function

1. INTRODUCTION

1.1. Overview of Gaia

Gaia is an ESA cornerstone mission due for launch in 2011 with the aim of mapping the positions and determining the motions of around one billion stars to an unprecedented accuracy. The Gaia satellite will be placed at the L2 Lagrangian point of the Earth, Sun, Moon system, and face away from the sun. As the satellite spins on its axis, two telescopes will scan the sky, with the stars being detected on a shared focal plane. The focal plane will be the largest array of CCDs ever flown in space and consist of 106 CCD91-72 manufactured by e2v technologies and contain over 937 million pixels covering an area of $0.286m^2$. The prime contractor EADS Astrium will integrate these CCDs into the Gaia satellite.

The CCDs in the focal plane are used by various instruments:

1) Astrometric Focal Plane (AF): - This makes up the majority of the CCD array (9 columns of 7 CCDs) and is used to measure the position of stars.

2) Sky Mapper (SM): - The light from each telescope is first scanned down one of two SM columns of CCDs. Each column of SM CCDs is associated with one of the two telescopes and so makes it possible to determine which field of view a star is in. These are the same CCDs as the AF.

3) Blue Photometer (BP): - Designed to provide low-resolution spectral data between 330 and 660nm. The BP CCD is an AF CCD that has enhanced sensitivity at the blue end of the spectrum.

4) Red Photometer (RP): - Like the BP but optimised for the red end of the spectrum, 650 to 1000nm. This is a deep depleted version of the AF CCD.

5) Radial Velocity Spectrometer (RVS): - This is a high-resolution integral field spectrometer to determine the third component of space velocity. It will use RP CCDs.

6) Wavefront Sensors (WFS) and Basic Angle Monitoring (BAM) instruments are also incorporated in the array. These are AF CCDs.

Figure 1 gives details of the telescope and focal plane arrangements. Further details of the Gaia mission and satellite can be found in references 1 and 2.

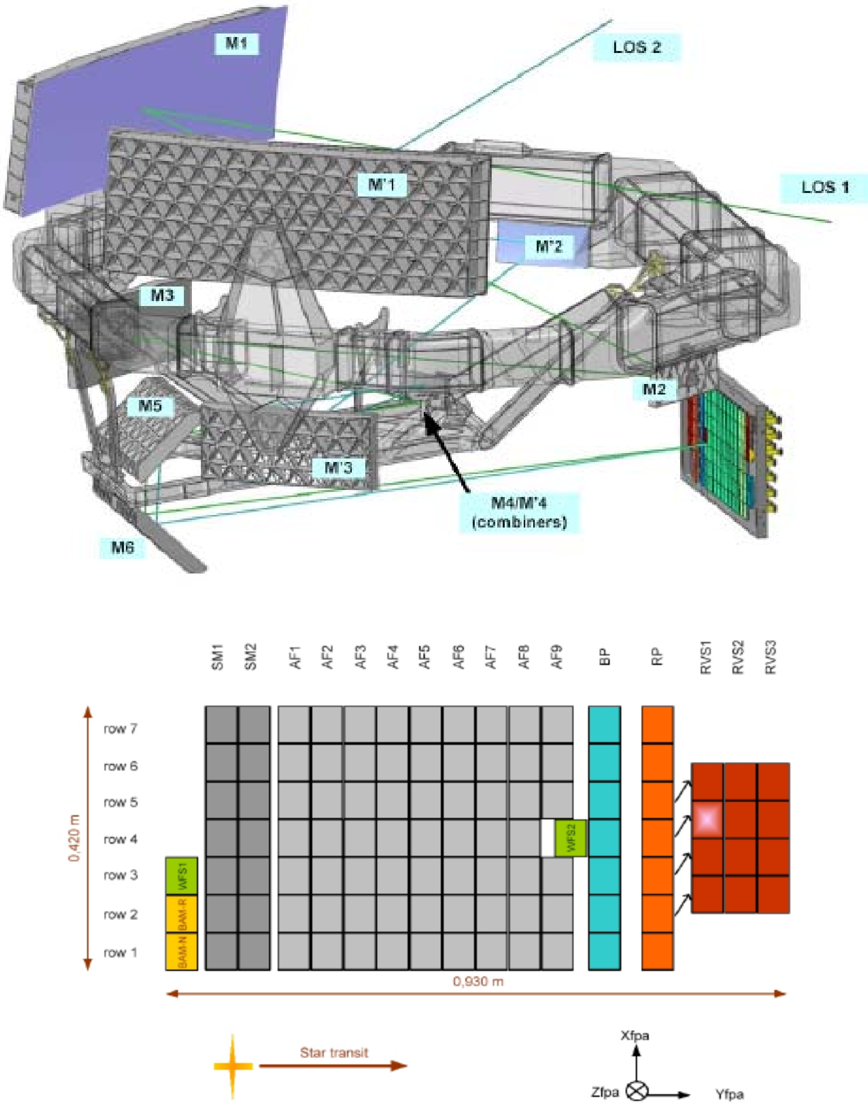

Figure 1: - The Gaia Telescope arrangement (top) and the focal plane layout (bottom) (Images courtesy of EADS Astrium)

1.2. The CCD91-72

e2v technologies won the contract to supply the CCDs for the Gaia satellite. These are custom designed, large area, back illuminated CCDs, designated as CCD91-72. They are 1966 (Horizontal) by 4500 (Vertical) pixels in size, with pixel dimensions of 30 (Horizontal) µm by 10 (Vertical) µm. To achieve this number of pixels, the chip is composed of 7 horizontal and 2 vertical photolithography sections that are stitched together. The CCD has charge injection and anti blooming structures. The chip is mounted on a three sided buttable package made of Silicon Carbide (SiC). On the fourth side of the package is a flexible connector, which is designed to minimise the dead space between devices making it effectively buttable on four sides. Figure 2 shows a photo of the CCD91-72.

Figure 2: - A CCD91-72. Note that a handling tool can also be seen in the photograph.

Since the telescopes will be scanning the sky as the satellite rotates, the CCDs will be operating in Time Delay Integration (TDI) mode, such that an image of a star will be continuously clocked in the scanning direction through the devices, at the same rate as the satellite rotates. This is different to traditional imaging where there is an integration time and a readout time. In such operation, if the imaged object is too bright and saturates the CCD, then the integration time can be reduced. This is not possible in TDI mode, where the number of transfers in the scanning direction and the clocking rate determine the pseudo-integration time. To allow the Gaia satellite to image objects of a wide magnitude range, the length of the device that is used for collecting light, the TDI length (i.e. the number of transfers in the scanning direction), can be selected by the use of separately connected parallel gates; these can either be clocked as a part of the parallel transfer sequence to allow signal charge to pass, or be held at the low level, blocking the transfer of charge. In this way, signal charge generated from the first lines of the device is prevented from being added to that generated in the remainder of the TDI length, effectively reducing the active TDI length. There are 12 TDI gates, allowing 13 different TDI lengths to be selected depending on the brightness of the object being imaged.

There are three variants of the CCD91-72 that are to be part of the Gaia payload. They all have the same chip architecture, but are optimised to be sensitive to different parts of the optical spectrum. The AF device is designed to work over a broad range of wavelengths. The BP device is designed for increased sensitivity at the blue end of the spectrum. To achieve this, the BP chip has special input surface passivation for enhanced response to short wavelengths (i.e. increased Quantum Efficiency) and an anti reflection (AR) coating optimised for the same wavelengths. The RP devices use deep depleted silicon so as to improve QE at longer wavelengths and an AR coating optimised accordingly.

1.3. The Gaia Project Phases

With the success of ESA's Hipparcos mission that was launched in 1989, a successor, Gaia, was first proposed in 1993. A two year Concept and Technology Study Phase concluded in 2000 that the Gaia mission was feasible. This lead to a Technology Demonstrator (TD) Phase between 2002 and 2005 when e2v technologies started designing, manufacturing and testing the first CCD91-72s, to assess their suitability for use in the Gaia mission. In the TD phase e2v technologies were required to deliver 20 Engineering Models.

Following a few minor redesigns based on the results of the TD Phase, 2006 saw the Evaluation Phase for the AF CCD91-72. The purpose of this was to environmentally test the CCD ahead of the Flight Model Manufacturing Phase where the CCDs that are to fly on the satellite were to be delivered. The Flight Model Manufacturing Phase began in 2007 for the AF CCD91-72.

The Evaluation Phases and the Flight Model Manufacturing Phases for the BP and RP CCD91-72, started a little after the AF, with BP and RP Evaluation running between January and September of 2007, with the Flight Model Manufacturing Phase starting in late 2007.

During the Flight Phase, a total of 130 flight grade devices and 40 engineering grade devices are due to be delivered.

1.4. Test Requirements

Table 1 summarises the different categories of tests that were required. Note that in parallel with the flight testing, lot acceptance testing (LAT) was performed to ensure that a consistent build standard was maintained throughout the course of the project.

Test Category	**Examples of Test**	**Reason for Tests**	**Stages test performed**
Electrical	DC Test Leakage Current on Input Gates	Check device functionality	All
Electro-Optical	Image, Amplifier Responsivity, Full Well Capacity, QE, Noise, Photo Response Non Uniformity, Photo Response and Dark Defects, MTF, Dark Signal	Check device functionality and that device meets performance specification	All
Geometrical	Device Dimensions, Device Flatness	Geometrical requirements are critical for a large array	All
Environmental	Thermal Cycling, Endurance Testing	Determine the life of the device under accelerated conditions	TD, Evaluation, LAT
Mechanical	Shock and Vibration	Check device will survive transport and launch	TD, Evaluation, LAT
Radiation	Exposure to proton and gamma radiation	Measure performance degradation when operated in space.	TD, Evaluation, LAT

Table 1: - Summary of Test Requirements

2. AN OVERVIEW OF THE GAIA TEST CAMERAS

The bulk of the testing of the Gaia devices was electro-optical testing. Electro-optical testing was performed to assess the performance of the devices when used in operation, and combined with Environmental, Mechanical or Radiation testing, it was used to determine how device performance was likely to change over the lifetime of the Gaia mission. The electro-optical testing is performed on bespoke test cameras, capable of cooling the devices to cryogenic temperatures representative of the optimum operating conditions to be used in the Gaia instruments. The cameras provide user defined waveforms and voltages to operate the CCD, provide light sources at multiple wavelengths, and allow acquisition and analysis of test images via PCs. Figure 3 is a schematic of a Gaia test camera and figure 4 is a photo.

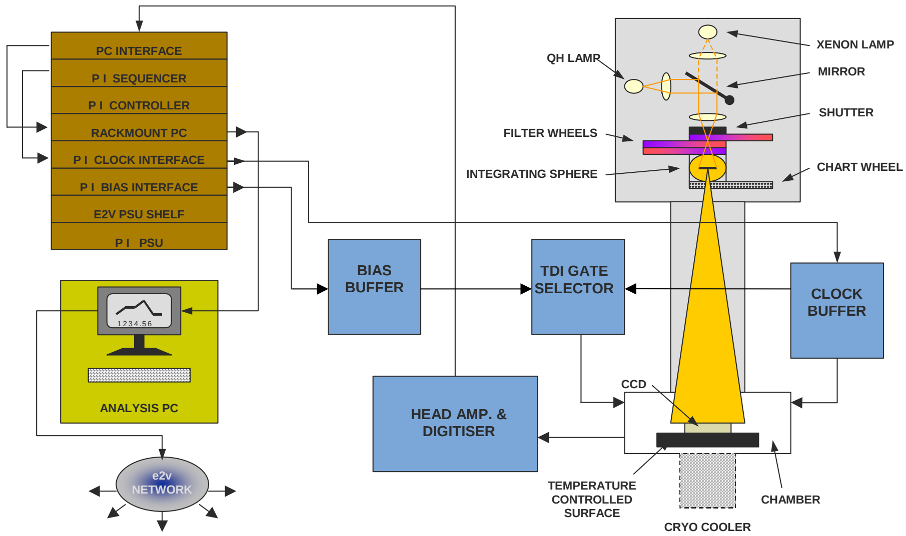

Figure 3: - A schematic of a Gaia Test Camera

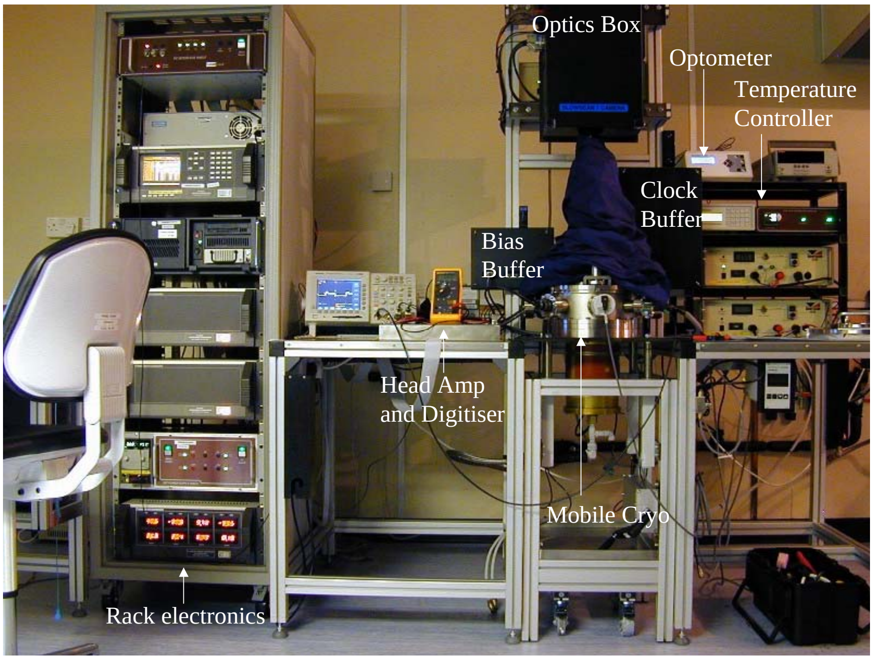

Figure 4: - A photo of a Gaia Test Camera

Since much of the test cycle time of a device is taken up with cooling the device down to cryogenic temperatures with liquid nitrogen, and then warming the device back up to room temperature (see table 2), the device is tested in a mobile cryostat that can be wheeled on and off the camera. Each camera has up to three mobile cryostats (cryos), so that a device can be loaded, the cryostat evacuated and cooled off camera. Whilst this is happening on one cryo, another can be tested on camera. Similarly, the cryos can be warmed and unloaded away from the camera. The cameras were also compatible with some non-vacuum, mobile chambers for making measurements at room temperature and for measuring MTF.

In the Evaluation and Flight Model Manufacturing phases there were multiple Gaia Test Cameras. In principle any cryo could have been used on any camera. There are two calibrations required on each cryo, an electrical gain calibration and an optical calibration. The electrical gain calibration is required to be able to convert the output signal from the camera into the number of photo-generated electrons in the CCD. The optical calibration is required to know how much light is incident on the device during any measurement. Due to the tolerances of the mechanical and electrical components that the cameras are assembled from, the calibration of a cryo on one camera will only be similar and not identical to the calibration of the same cryo on a different camera. Hence to keep the number of calibrations required down to a manageable level, each cryo is only calibrated, and therefore used, on a specific camera. Temperature calibrations were also performed on a few cryos to determine the offset between the temperature controlled surface (see figure 3) and the device. This was observed to be near identical every time that it was run, and the slight variation observed was well within the temperature tolerance that was required. Hence it was not deemed necessary to have the temperature calibration as a mandatory, periodic calibration.

3. TESTING CHALLENGES AND SOLUTIONS ENCOUNTERED DURING THE DIFFERENT PROJECT PHASES

There were a number of issues that arose in the TD Phase that if they were not addressed, would have seriously impacted on the ability to test the required number of devices for flight whilst still maintaining a high quality of test data. These points are addressed in the following sections.

3.1. Volume of testing

The testing of the AF devices in the TD phase took nearly two years, and in this phase of the project only 20 devices were required for delivery. With the increased number of devices required for the flight phase, and the fact that the evaluation had to be performed before flight model testing could start, continuing at this rate of testing would have put the launch date in severe jeopardy. There were a number of areas that were addressed, to severely increase the rate of test.

The biggest change between the TD and subsequent phases was the number of test cameras available. During the TD phase, only one test camera was available. This had been developed specifically for testing Gaia devices, and was very successful in proving the effectiveness of the mobile cryostats to increase device throughput on the camera. However one camera with four cryos was not going to provide enough test capacity. Hence prior to and during the evaluation phase, more test cameras were brought online in time for the flight model manufacturing phase. By the time the flight model manufacturing phase had started, there were five test cameras, with a total of 15 cryostats dedicated to testing Gaia devices. A new clean room was needed to house these cameras, and this was built with liquid nitrogen plumbed in to keep the cryos cool. The new test cameras were very similar to the original test camera, but minor issues with the original test camera were resolved. Where possible the original test camera was upgraded. These upgrades included fitting of a photo diode to the integrating sphere (see figure 3 and section 3.2), installing an LED to the optics box for the full well capacity tests (see 3.4), and fitting a virtual oscilloscope for the measurement of CCD waveforms (see 3.5). New chambers for measuring MTF were also developed, that could interface with the cameras in the same way as the cryos. Though MTF was measured in the TD phase, it was laborious and time consuming and required a significant amount of operator input. The new MTF chambers allowed automatic measurement (see 3.3).

The software that performs the acquisition and the analysis of the CCD images is bespoke, written by e2v technologies using LabView. The clock drive is controlled by sequencer software written by e2v using the code language of the Pulse Instruments sequencer hardware. Though in the TD Phase it performed the task it was designed to do, the software required a significant amount of user intervention, and was not as robust as desired. The software was completely overhauled to make it much more robust and to allow a greater amount of automation. This meant that instead of requiring one operator per shift to run one camera, it became possible for two operators per shift to take care of five cameras. The analysis software was also automated, and a database was used to record all the test results. The data could automatically be extracted from the database and put in a presentable form for dissemination to the customer, considerably reducing the amount of time that would have been spent collating this data manually.

Dealing with the quantities of test data that Gaia produced was also a challenge. Around 1Giga Byte of data was produced from the test data of each device that underwent the standard production tests. Significantly more data was acquired for a device undergoing Evaluation or LAT testing. All this data needed to be archived in a secure way, so dedicated servers with Tera byte capacity were used.

Between the TD and flight phases, each individual test was reviewed to see if it could be made more accurate and be performed in a shorter space of time. For production flight testing, some lengthy tests such as antiblooming and charge injection, were reduced in scope, steering away from being a full characterisation of the parameter, to being a functional check that the device was performing to the specification for that parameter. Characterisation testing was reduced to a much smaller subset of devices, rather than being performed on every flight device. Details about some of the major and innovative changes to tests are detailed in the following sections.

The final factor that allowed for a significant increase in the test rate was the human one. A dedicated team, consisting of engineers, and operators was set up to perform the Gaia testing. The operators were responsible for collecting the test data, the engineers for co-ordinating the testing and reviewing the results. Not only were the usual detailed test procedures put in place, but operator education was also vital so that the operator not only knew what they were doing and how to do it, but why they were doing it. To engage the operators, the basic operation of a CCD and the details of the Gaia mission were presented to them. Feedback from operators was actively encouraged, either informally or through regular meetings. All this led to excellent working relations between everyone involved in the testing of devices. Without the dedication, engagement and eagerness of the test operators, the project would not have been as successful.

3.2. Quantum Efficiency (QE)

During the TD phase, the variability of the QE measurements of the 20 AF devices supplied was larger than expected, and the shape of the QE curves was not as predicted, with a step noted in the curve between 550 and 600nm and another between 650 and 700nm (see figure 5). At 600nm one device was measured to have a QE of 78% whereas another had a QE of 96%. This was attributed mainly to limitations in the test method, with two areas of concern:

1) The optical calibration was only performed every 3 months or when a tungsten halogen lamp on the camera was changed. It is known that the light output of tungsten halogen lamps will drift as they age. The ageing of the lamp combined with the three month calibration interval was a significant factor in the variability of the measured QEs.

2) The step in the curves coincided with a change from one type of Neutral Density (ND) attenuating filters to another. Attenuating filters, in combination with the integration time, were used to control the amount of light falling on the device. It was unclear why a change in ND filter should have caused a step change in the measured QE, as this should have been accounted for in the optical calibration, but it was desirable to eradicate if possible.

To resolve these issues, two changes were proposed and implemented for the Evaluation phase onwards. These were:

1) Live calibration of the light level. A photo diode was mounted in the integrating sphere of the camera (see figure 3). This took a reading of the light level in the integrating sphere simultaneously to the QE of the device being measured. A periodic optical calibration was performed to determine the ratio of light

measured in the integrating sphere to the light incident on the device. This ratio is very stable since it only depends on geometric effects (e.g. how far the device is from the integrating sphere photo diode) and the materials (e.g. cryo window) between the device and the integrating sphere diode, both of which do not change. It does not depend on the brightness of the lamp so the effects of the lamp drift have been eliminated (provided the bulb in the lamp hasn't blown!)

2) To attenuate the light, ND filters were eliminated, by adjusting the size of the exit aperture of the camera's optics box. For wavelengths where the lamp output was low, the aperture size could be increased, and vice versa. This could be done automatically by the software. After every lamp change, the aperture sizes were reset to give approximately half CCD image full well signal level, with enough margin to accommodate lamp drift, whilst still using a relatively short integration time to keep the test time to a minimum.

Both these solutions had a remarkable effect on the measured QE (see figure 6). Regardless of the cryo it was in or test camera that a device was measured on, the QE results are now very consistent and in agreement with theoretical models of device QE. The new optical calibration regime of measuring the ratio of the light in the integrating sphere was so successful and stable, that the calibration interval was later extended from three months to six months for each cryo.

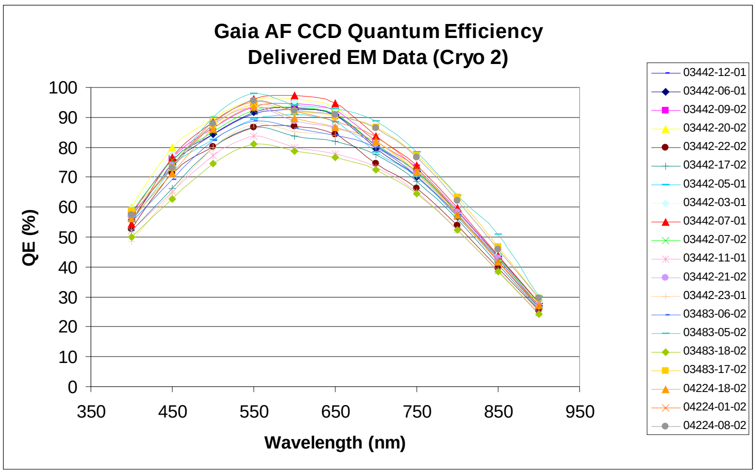

Figure 5: - Measured QE curves for the 20 AF devices delivered in the TD phase.

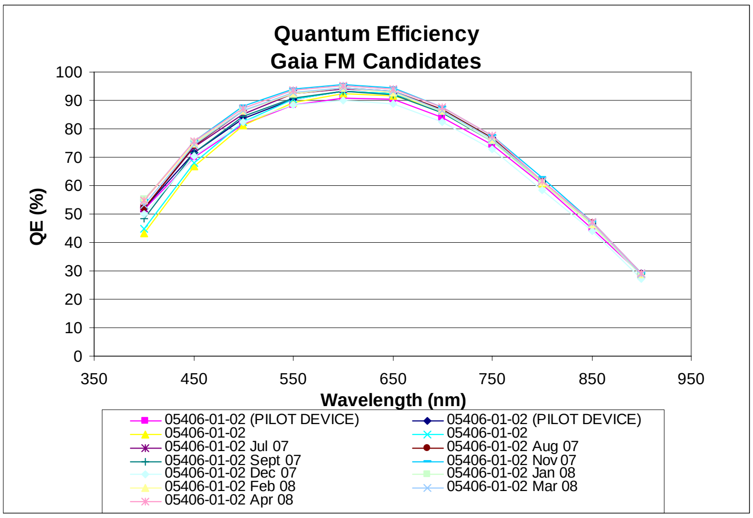

Figure 6: - Multiple QE measurements of the Flight Phase Control Device taken between February 2007 and April 2008. Note this curve includes measurements from several different cryos and different cameras. The spread at the blue end of the spectrum shows the inherent variation of the sensitivity of the device surface, e.g. with molecular absorption.

3.3. Modulation Transfer Function (MTF)

For the Gaia satellite to achieve the required angular resolution (equivalent to measuring the diameter of a human hair at a distance of 1,000km [2.]), the spatial resolution or MTF of the CCD is a vital parameter. However MTF has historically been a very arduous measurement to perform.

3.3.1. MTF measurement theory

There are many ways in which MTF can be measured. The method employed by e2v technologies is based on the Vernier Technique. The MTF of a CCD can be derived (Fourier Transform) from the Line Response Function (LRF) of an optical system. This is determined using the Vernier technique in which a narrow silt, (width less than pixel width), is focussed on the CCD. The focussed line image is rotated to a desired angle, see figure 7. The pixel signals obtained from the rows containing the upper and lower column crossing points are also shown in figure 7.

This spread of signal across the pixels defines the LRF with a resolution of sub pixel pitch and hence the MTF can be determined. The MTF is influenced not only by the design and construction of the CCD but the wavelength of the incident light and its mode of operation (depletion depths etc). Exact details of the mathematics involved and a more detailed description can be found in reference 3.

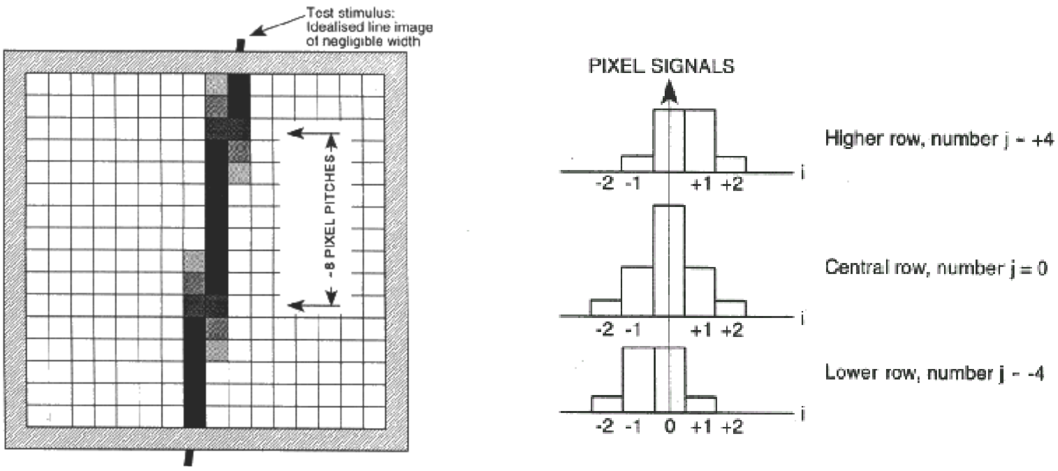

Figure 7: - Schematics of MTF Slit Image (left) and signal in top, middle and bottom row of the angled slit image (right)

The CCD is illuminated with a slit image, of length sufficient to cover more than 16 pixels. The slit image is narrow enough for all of the width to be contained within one pixel. The slit is aligned so as to be at a small angle with respect to a CCD column, such that going from the bottom row of a 16 x 16 pixel array to the top of the array, the slit starts in row 1 centred on a pixel in column n and ends up on row 16 centred on a pixel in column n+2, thus fully traversing row n+1. The 16 x 16 array of pixels is read out of the CCD and a polynomial reconstruction of the line-spread-function is computed. From the discrete Fourier Transform of the line-spread-function, the MTF is obtained.

3.3.2. MTF Test Evolution

The MTF measurement requires a specialised set of optics that allow fine focus of a narrow slit on a CCD at multiple wavelengths, the ability to move the position of the slit on the CCD, and the capability to adjust the angle of the slit with respect to the pixel array of the CCD. It was apparent at an early stage that it would be difficult to interface such an optical system with the standard test cryos. Thus a separate MTF chamber was developed that could be used on the camera in place of a cryo.

The original MTF chamber used in the TD Phase was a manual instrument. The MTF chamber was peltier cooled to around 10ºC below the ambient temperature, mitigating the need for a vacuum housing. A de-magnified slit was projected onto the device, with a lamp providing the light source and a mechanical shutter providing the blacking out during readout. Optical filters were used to provide different wavelengths. Three vernier screw gauges were used to move the lens in the x, y and z directions to adjust the position of the slit on the CCD (x and y directions) and the focus of the slit. Whilst the CCD was clocking out slit images, the operator was required to adjust the vernier screw gauges to get the slit in the correct position and as sharply focused as possible. With three dimensions to adjust, this required a significant amount of skill by the operator, to get a slit image for an MTF measurement particularly considering that the positioning accuracy of the slit that is needed with the Vernier technique is of the order of a few microns (i.e. the pixel size). With the slit focused and in the correct position on the device, the operator would then have to use another screw gauge to adjust the angle of the slit. The measurement could then be taken. With one wavelength complete, the optical filter would be changed ready to measure the next wavelength. However changing the filter would induce some movement in the screw gauges, and the operator would then have to reset the slit. It could take an hour or more to set the slit up for each wavelength, so measuring the MTF at several wavelengths would take at least an operator shift. This was immensely frustrating for the operator and obviously wasn't a very time efficient way of measuring MTF, particularly in the context of the large quantities of devices that were being planned to be tested in the flight phase.

A new MTF chamber was proposed for the flight phase, and was developed during the evaluation phase. The aim of the new MTF chamber was to provide a user friendly, accurate, repeatable and relatively quick system for measuring MTF using the Vernier Technique. There were two ways that this was achieved: increased automation of the test and vastly improved mechanical stability.

Automation was achieved by using computer controlled x, y and z stages that instead of moving the lens, moved the actual device, to focus the slit and get the slit in the correct position on the device. The operator was simply required to tell the computer via newly written LabView software where the centre of the slit was, and the computer would move the device to the relevant position. A focusing algorithm would then find the optimum slit focus by analysing the imaged slit width. The correct slit angle was then automatically found. To reduce the amount of dark signal in the slit images, a more effective peltier system was installed to allow the test to be performed at around 25ºC below ambient. Dry nitrogen purging is used for controlling condensation.

Mechanical stability was improved by making the system far more solid. With the device, rather than the lens being moved, the system had far more inertia. Also when switching from one wavelength to another, instead of the operator having to physically change the optical filter, a combination of LEDs and a filter wheel were used so that switching from one wavelength to another could automatically be done. The LED could be pulsed, avoiding the need for a mechanical shutter. All this meant that the system was less likely to be disturbed by vibrations.

The success of the new MTF chamber was such that instead of taking an operator shift or longer to take measurements at all the six required wavelengths, a device could be loaded, cooled, tested at six wavelengths, and unloaded within an hour. The new MTF chamber produced results consistent with those of the previous kit, but was far more repeatable. Two automatic MTF kits were built for the flight phase, which were identical apart from the wavelengths of light that could be supplied, allowing the three variants of the CCD91-72 to be tested over different wavelength ranges. Figure 8 is a photo of the new MTF chamber and a plot of some results from typical AF, BP and RP CCD91-72s.

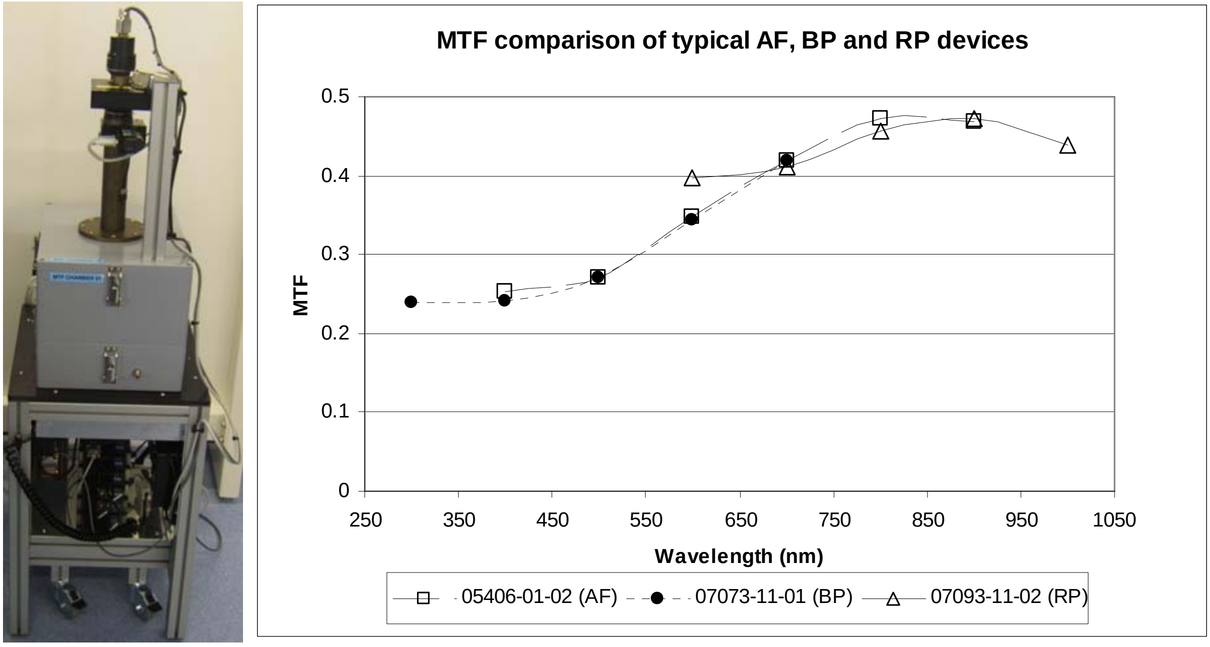

Figure 8: - A photo of the new automated MTF chamber (left) and MTF data (right) for a typical AF, BP, RP CCD91-72 from the Flight phase measured in the along track, small pixel dimension (10um) direction. MTF across track, in the dimension of the larger pixel dimension (30um), is typically 0.45 to 0.55 for all device types.

3.4. Full well and linearity

An ideal CCD is a perfectly linear detector (e.g. doubling the input signal, doubles the output signal) until full well is reached where the device output signal becomes limited. By measuring the non-linearity of the output signal with increased input signal, the full well can be determined when the non-linearity makes an abrupt departure from the predicted value. e2v technologies have used this method to determine both the image full well and, by binning pixel signals, the output node capacity. The image full well test takes 20 illuminated flat field images with increasing integration time, such that the final few image frames will be saturated. The signal level in each image, in electrons, is compared to a best fit straight line to the near linear part of the signal versus integration time curve. The percentage deviation of each data point from this best fit straight line is the non linearity. The non linearity is plotted against the signal level, with linear interpolation between data points. The signal level where this curve is first greater than 1% is defined as the image full well. The output node capacity test is identical, except that it involves binning image pixels into the larger capacity register elements. The same analysis is performed, but with a 5% limit, but it does have the disadvantage that it is not possible to determine whether it is the register elements that are saturated or the output node. A further test with serially binned pixel signals could determine this but in practice this is not a problem as it is only the minimum of these two that is of concern, and it is this that is measured.

During the TD phase, the full well tests were done using shuttered illumination from a tungsten halogen light source. The non linearity was quoted at the full well specification. However it was not possible to have the required dynamic range in a single test. The test was required to confirm that the CCD image area pixels non-linearity was less than 1% in the signal range of 200 electrons to 190,000 electrons, and the output node linearity error was less than 5% in the signal range of 800 electrons to 240,000 electrons. The wide dynamic range meant that from the 1st to 20th image frames, the integration time would have to increase by at least a factor of 1,000. Now the test would take a vast amount of time, unless the initial integration time was very short. The initial integration time was chosen to be 100ms, but this was not compatible with shuttered illumination, since the shutter response time (i.e. the time to open and close) is comparable to this integration time and there is variation on this response time of a few milliseconds. Any small absolute deviation in the signal level due to the shutter timing error, on a small signal level, would result in a large percentage error, making it impossible to confirm that the devices met the linearity specification using this method in a reasonable length of time.

The solution was to use pulsed LED illumination thus removing the need for a mechanical shutter. The LED has a negligible response time, and the response time error is thus insignificant when compared to the 100ms integration time. To get an initial signal level of 200e with a 100ms integration time, at the start of the test, the size of the exit aperture was adjusted by the software in a similar way as is done for the revised QE test (see 3.2).

It is also necessary when covering a large dynamic range to improve on the conventional best-fit line technique, or inevitably the smallest signal level will show the largest deviation when expressed as a percentage of signal level. A revised mathematical algorithm was used to perform line fitting for minimised percentage deviations.

One other problem connected with this test was to get a very stable zero reference level to determine the signal level caused by light. To achieve this light leakage into the cryo was completely eliminated, and the voltages of the device were adjusted to provide optimum device resetting. If the device was not quite being reset properly, the mean zero signal level could vary by a few electrons from one image to the next, causing the non-linearity at low signal levels to be higher than desired. Figure 9 shows linearity plots showing the progress of this test.

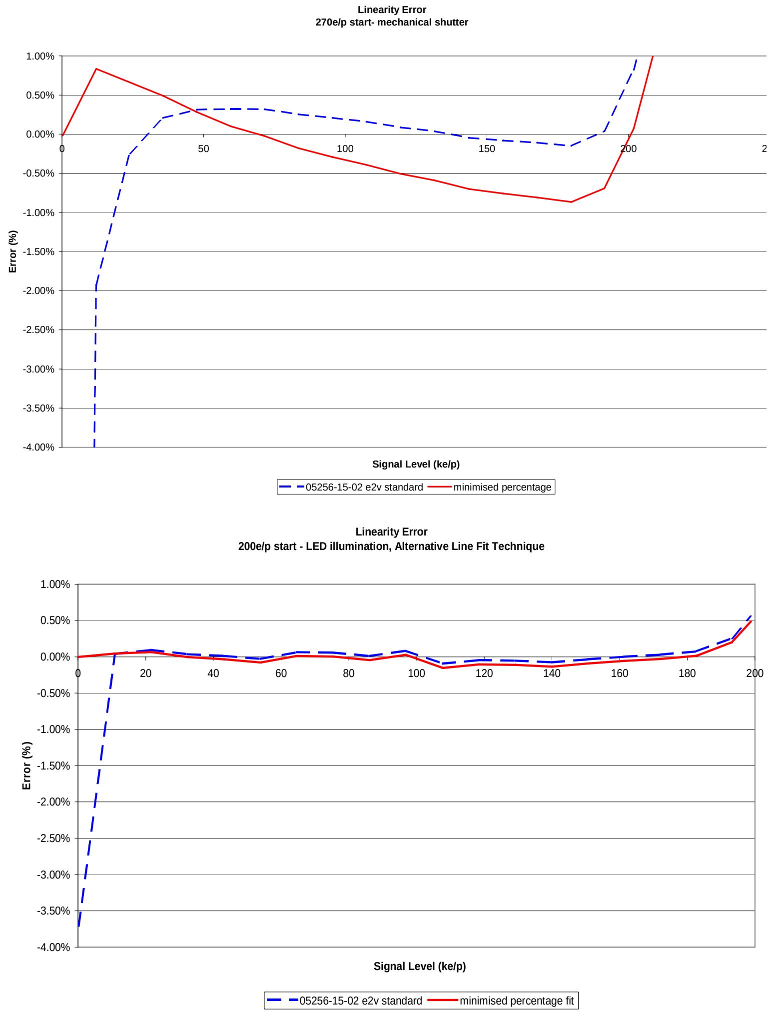

Figure 9: - Linearity plots over a signal range of 200 to 190,000 electrons using shuttered tungsten lamp (top) and LED illumination (bottom). The dashed lines are using standard line fitting where the absolute residuals are minimised, the solid lines are where the percentage residuals have been minimised in the line fitting. Both plots use data from the same device.

3.5. Waveforms

In the TD phase, the waveform measurements were made on a Cathode Ray Oscilloscope (CRO), and the data manually read off the CRO's small screen. For the evaluation phase onwards, the use of a virtual oscilloscope driven by a PC, meant that the data was in a form that could be conveniently accessed by a PC, and so specific software was written in MATLAB to determine waveform features such as the amplitude of the reset feedthrough and video level settling time. This lead to not only the waveform test being quicker, but also more consistent as it was not relying on an operator to make arbitrary determinations of where different parts of the waveforms were from looking at the CRO's small screen. Figure 10 is an example of the improved waveform analysis.

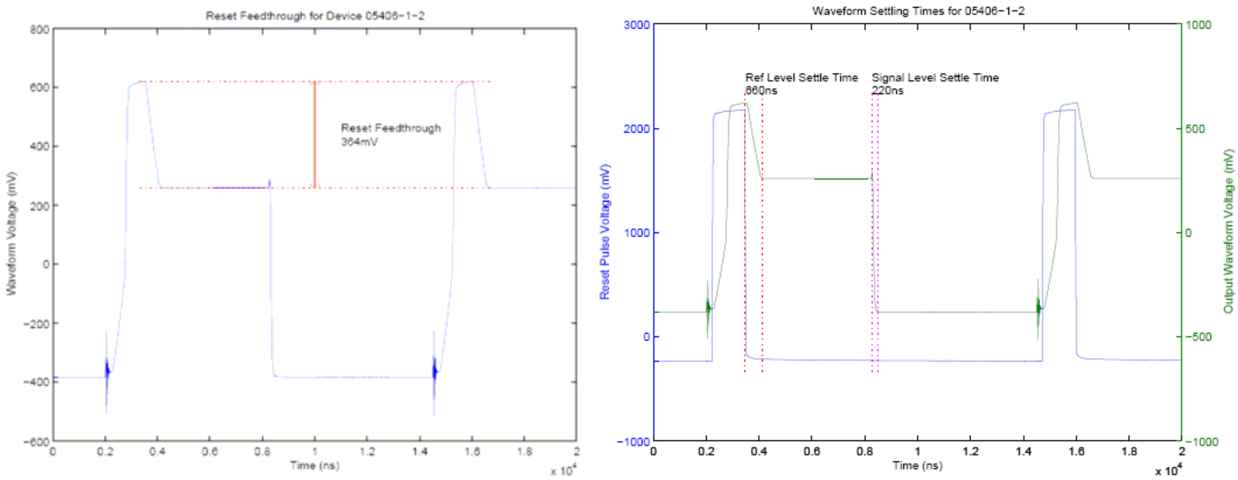

Figure 10: - Examples of waveform measurements using a virtual oscilloscope and automatic software analysis

3.6. Radiation Testing volume

Since the Gaia devices will operate in space, knowing their performance degradation after exposure to radiation is vital. This was characterised in the Evaluation Phase. During the flight model manufacturing phase, e2v technologies were required to perform radiation testing on at least one device for every silicon wafer batch that produced a flight deliverable device. Given the quantities involved in Gaia, there were many wafer batches, so potentially having to perform radiation LAT on one CCD91-72 per batch would have been very costly. The solution came in having radiation test vehicles on each wafer, designated by e2v as the CCD221. The CCD221 was a device with the same architecture as the CCD91-72, but a lot smaller, only having 1440 rows and 224 columns. Because it was smaller it only had two TDI gates. Also the CCD221 could be packaged in one of e2v technologies' standard ceramic dual in-line packages.

A cryo was dedicated to CCD221 testing, and allowed for four devices to be loaded at the same time. Being a smaller device enabled the device to be tested significantly quicker than the CCD91-72 as the readout time was much reduced. Having four devices loaded into a cryo simultaneously also meant that the number of cooling and warming cycles per device was reduced by a factor of four, again significantly reducing the test time.

4. IMPROVEMENTS IN THE TEST CYCLE TIME

Section 3, detailed how the tests were improved between the TD and Flight phases. Obviously there has been a significant improvement in the quality and repeatability of the test data, but there has also been a dramatic reduction in the test cycle time. Table 2 compares the test times for each of the tests used for post burn in production flight phase testing of the CCD91-72, to the time it took to perform that test in the TD phase. As can be seen the total time that a device spends on camera for post burn in testing has more than halved. (Note burn in is a process where the device is biased and held at an elevated temperature for several days. Before undergoing burn in a device will undergo a limited set of electro-optical tests. This was the same in the TD phase and is not considered in table 2.)

Test Name	**TD Test Time**	**Flight Test Time**	**Comment**
Device Loading, Cryo Pumping and Cooling.	4 hours	4 hours	Note this time is off camera and does not occupy electronics systems.
Image Test	30 minutes	15 minutes	In flight phase additional image test in dark added.
Amplifier Responsivity	5 minutes	5 minutes	
Image Area Full Well	1 hour 30 minutes	1 hour 30 minutes	
Output Node Capacity	1 hour	1 hour	
Photo Response Defects	10 minutes	10 minutes	
Traps	Not performed	10 minutes	
Waveform Features *	30 minutes	10 minutes	
Static Bias Current	5 minutes	5 minutes	
Output Impedance	10 minutes	10 minutes	
Photo Response Non Uniformity	30 minutes	30 minutes	Time quoted is for measurement at all 3 wavelengths
QE *	30 minutes	45 minutes	AF time quoted for measurement at all 11 wavelengths. More wavelengths measured for BP and RP variants
TDI Gates	50 minutes	50 minutes	Tests functionality of each TDI gate
Antiblooming	3 hrs 30 min	15 minutes	Flight phase test is a functionality check only. TD phase was a full characterisation
Charge Injection	1 hour	40 minutes	Flight phase time assumes that test four different voltage configurations are required to find settings for device to be in specification.
Noise	5 minutes	5 minutes	
CTE	15 minutes	15 minutes	
High Speed CTE	Not performed	5 minutes	
Dark Signal and Defects in Darkness	4 hours	1 hour 10 minutes	Includes time to warm cryo to test temperature, TD phase test performed at two temperatures, flight phase test one.
Cryo warming and Device Unloading	4 hours	4 hours	Note this time is off camera and does not occupy electronics systems.
MTF *	8 hours	1 hour	Time quoted for measurement at 6 wavelengths and includes loading, cooling and unloading time.
Room Temperature Electro-Optical Tests	Not performed	30 minutes	To compare with Electro-Optical Tests performed during device integration into focal plane array
TOTAL TIME DEVICE UNDER TEST	**30 hr 40 min**	**17 hr 40 min**	Includes loading, cooling, warming and unloading device from cryo.
TOTAL TIME ON CAMERA	**22 hr 40 min**	**9 hr 40 min**	Excludes loading, cooling, warming and unloading device from cryo.

Table 2: - A comparison of the test cycle times between the TD and flight phases. Tests marked * required significant operator intervention in the TD phase, but not the flight phase, freeing the operator to test on other cameras.

5. CONCLUSIONS

Gaia is a very ambitious space based observatory requiring an unprecedented number of CCDs in a focal plane array. This presented e2v technologies, who have designed and manufactured the CCDs, with significant challenges in meeting the requirements of the mission in terms of device quality and quantity, particularly from a testing perspective. Through developing and expanding the existing test capability with both technical and organisational solutions, the quality of the test data has not only improved significantly but also the test cycle time drastically reduced. Because of these improvements and the quality of the CCDs, within a few months of the start of testing, e2v technologies were having CCDs accepted at an average rate of 10 per month meaning that a vital part of the Gaia payload should be available in plenty of time to be integrated into the satellite for the proposed launch in 2011.

ACKNOWLEDGEMENTS

The authors would like to acknowledge all those in e2v technologies who have been involved with the Gaia project as well as ESA and the prime contractor EADS Astrium for providing e2v technologies with the opportunity for working on such a groundbreaking project.

REFERENCES

1. Gaia: - Taking the Galactic Census, Overall Science Goals, Revision 2, 13/2/06, Michael Perryman / ESA
2. www.esa.int/science/gaia
3. Technical Note on the MTF of CCD Sensors, A1A-CCDTN105, Issue 5, e2v technologies