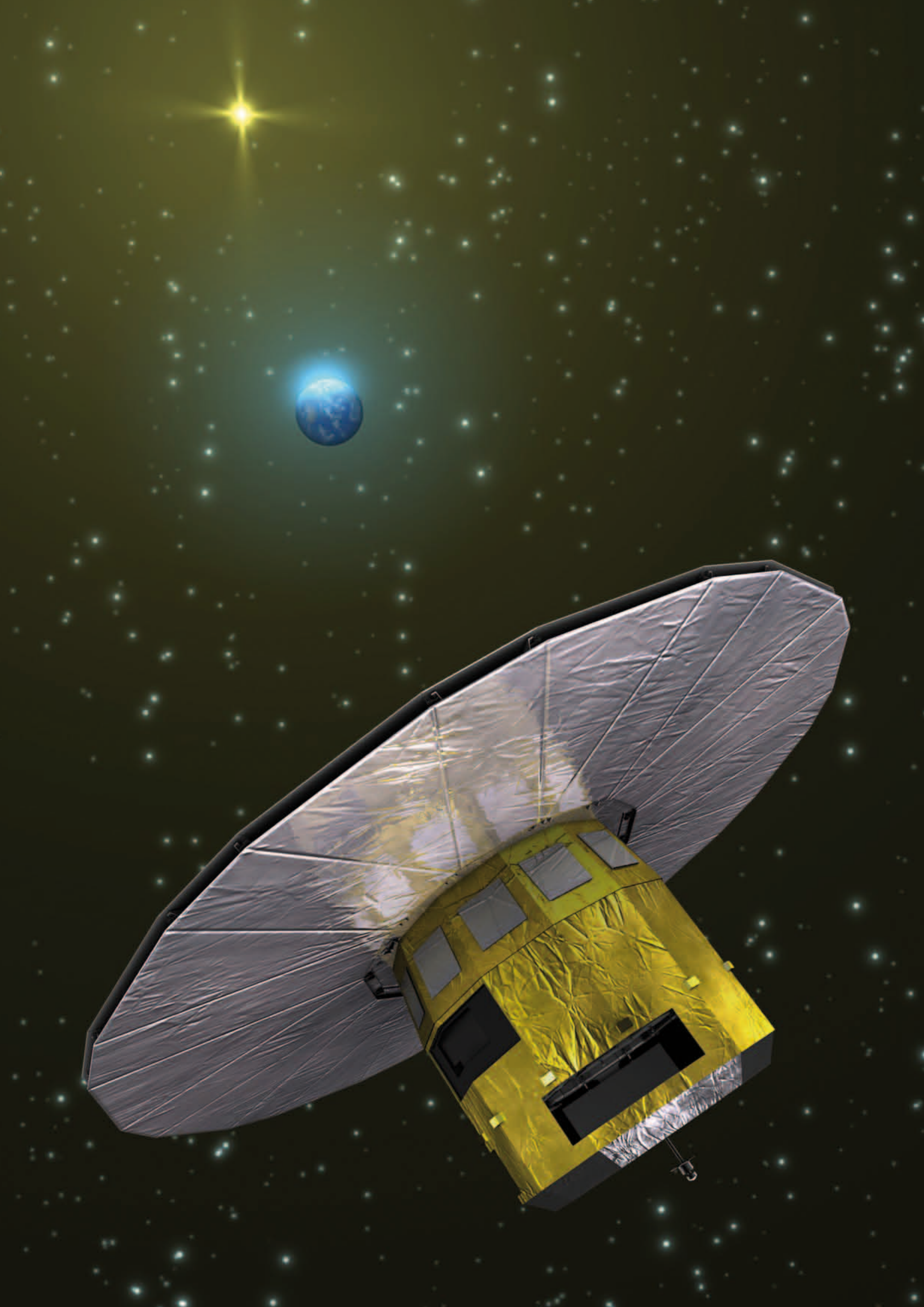

→ ESA'S 'BILLION-PIXEL' CAMERA

The challenges of the Gaia mission

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Gaia is ESA's global space astrometry mission, designed to map one thousand million stars and hundreds of thousands of other celestial objects in our galaxy, so its camera will have to be something truly special.

Indeed, when Gaia lifts off from ESA's Spaceport in Kourou, French Guiana, by the end of 2011, it will be carrying the largest digital camera in the Solar System.

Combined with the simultaneously measured photometric and spectrometric information, the Gaia data set will provide a vast improvement of our knowledge of the early formation of our galaxy and its subsequent dynamical, chemical and star-forming evolution.

As it spins gently in its orbit, 1.5 million kilometres away from Earth, Gaia will scan the entire sky for stars, planets, asteroids, distant galaxies and everything in between. Conducting a census of over a thousand million stars, it will monitor each of its target stars up to 70 times over a five-year period, precisely charting positions, distances, movements and changes in brightness.

The aim is to detect every celestial object down to about a million times fainter than the unaided human eye can see. To do that, it needs a large camera. In fact, there will be over 100 separate cameras in Gaia, tiled together in a mosaic to register every object that passes through the field of view. Scientists call each of these individual cameras 'charge-coupled devices', or CCDs.

Each CCD is itself a major piece of hi-tech kit that converts light into electrical charge and stores it in tiny pockets known as 'pixels' until the computer reads out this information. With about 1000 million pixels, Gaia's focal plane is the largest digital camera ever built for spaceflight.

Progress made and difficulties overcome

Gaia's impressive task meant that several key technologies needed to be pushed forward significantly. The performance of some optical equipment, e.g. mirrors and detectors, was subject to specific technology developments but, in particular, the size of Gaia's novel CCDs presented some unique manufacturing challenges.

Early technology development started in 2000, but by 2005 the level of confidence in these large-size CCDs was high enough that mass production could be envisaged. The same year, a procurement contract was placed with e2v technologies (UK) for the astrometric-type CCD and extended, in early 2006, to the 'blue' and 'red' types of CCDs (differences due to the wavelength range for which they are optimised).

Thanks to this early start, the production is now well ahead of the required dates for the satellite. About two thirds of the total amount of CCDs is already available for the spacecraft programme, this includes more than half of the flight-quality models.
The sensitivity of CCDs to radiation in space was the most critical problem encountered to date (i.e. from solar activity such as solar flares or 'coronal mass ejections'), and this was even considered a major 'show-stopper' for the whole mission if not adequately mitigated.

Astrium SAS, the prime contractor, proposed a comprehensive CCD test and characterisation programme. This programme was reviewed and accepted in close collaboration with the scientific community and is now in its

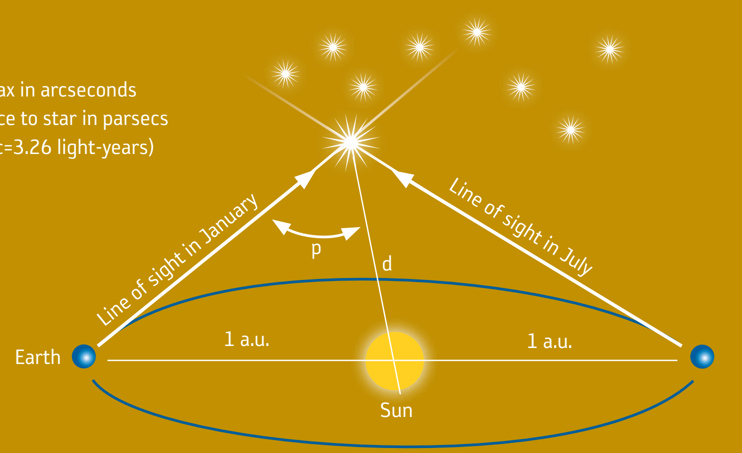
→ Measurement principles of astrometry

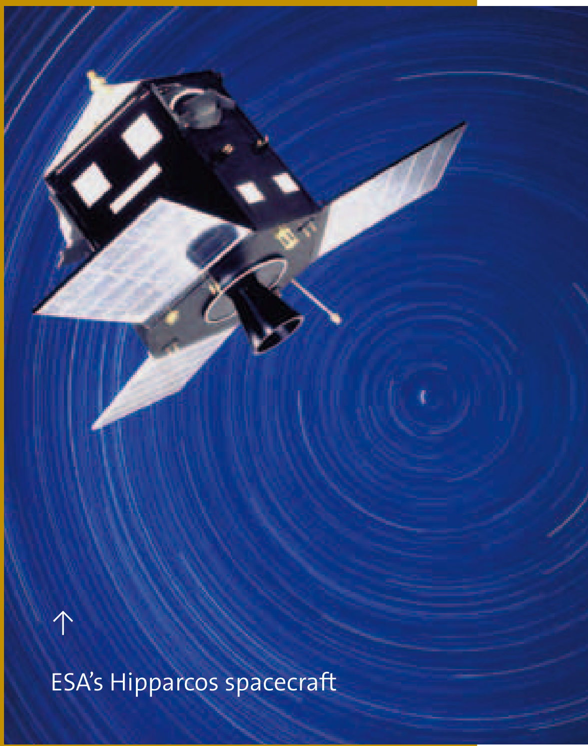
Astrometry, the science of determining the position of objects in the sky, has been predominantly performed from Earth within the 'narrow' field of view of a telescope.

This method relies on measuring the apparent displacement over time of nearby stars compared to more distant reference stars. This displacement, known as 'parallax', is caused by the changing direction of view of an observer as Earth orbits around the Sun. The inherent measurement errors only permit to achieve accuracies of the order of a milliarcsecond, thus three orders of magnitude worse than the expected Gaia accuracy.

Gaia's technique is 'wide-angle' astrometry, which allows direct measurement of the absolute parallax. This technique is based on continuous star detections in two fields of view separated by a large angle which needs to be known and maintained at a very high accuracy over the entire mission lifetime. This technique was successfully demonstrated on Hipparcos, ESA's first astrometry mission, launched in 1989.

d=1/p
p= parallax in arcseconds
d=distance to star in parsecs
(1 parsec=3.26 light-years)





↑ ESA's Hipparcos spacecraft

execution phase. Based on detailed analysis of early results, it is expected that the radiation effect can be calibrated and so removed from real measurements in space.

The associated data processing is currently in its design phase. The process will not be simple, because many CCD parameters need to be taken into account, but it should ensure that measurement accuracy is not impeded by radiation effects.

Many lessons have been learned during the CCD production; not only related to the development and validation of new CCD technologies, but also linked to the effort associated to the establishment of a 'mass production' for space hardware.

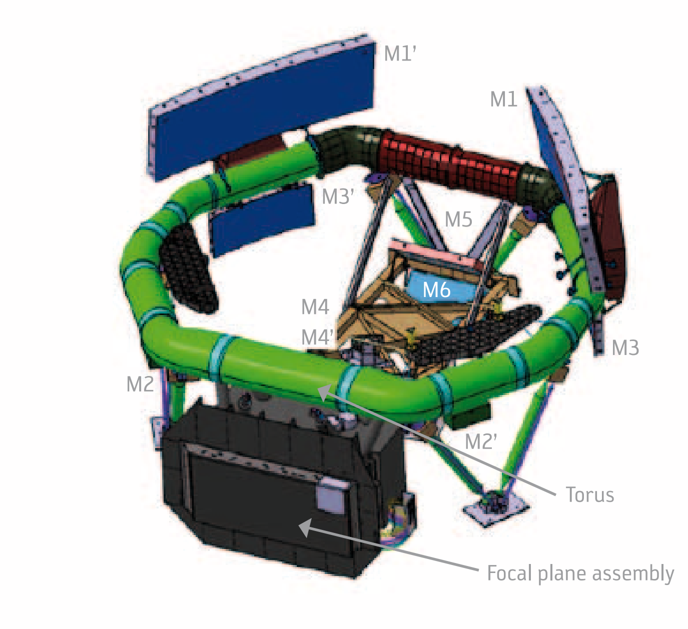
The most obvious lesson learned is that the production of new technology items must begin as early as possible, even before the spacecraft programme starts and must remain very closely linked to the spacecraft project. For Gaia, this early start means that the procurement and availability of the CCDs, initially considered to be the most critical activity, has been downgraded to a relatively smooth production process.

Despite several unexpected problems emerging during the CCD production phase, the associated healthy schedule meant that problems could be resolved with low stress and without excessive time pressure.

Gaia spacecraft and payload in detail

Gaia's star measurement principle relies on the repeated observation of star positions in two fields of view. The spacecraft rotates slowly at a constant angular rate of 1 degree/min around the spin axis, therefore completing four great circles on the sky in one day. In addition, the orientation of the spin axis is modulated by a slow precession around the Sun-to-Earth line with a period of 63.12 days that enables the observation of about 70 transits of the same celestial object over the five-year mission duration.

The achievement of the final product of the mission, a catalogue containing the accurate position and true motion



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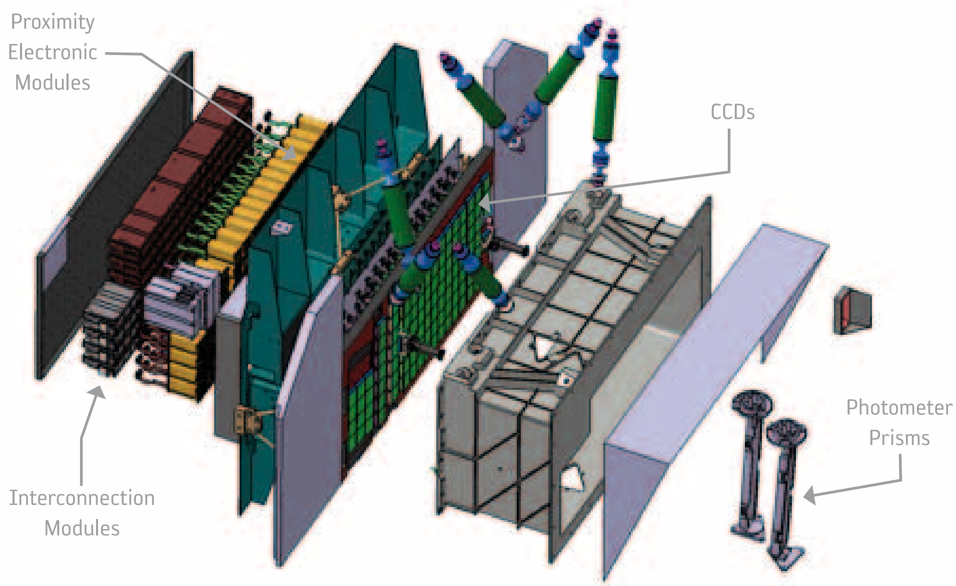
The Gaia Payload Module. The focal plane is hanging on the 'optical bench torus' made of silicon carbide. The optics consist of 10 mirrors and the refractive optical elements. Mirrors M1, M2 and M3 form one telescope and M1', M2', M3' the other telescope. The subsequent set of mirrors M4/M4', M5 and M6 combine the light from both telescopes and direct it to the focal plane assembly. The fields of view are 106.5° apart (Astrium SAS)



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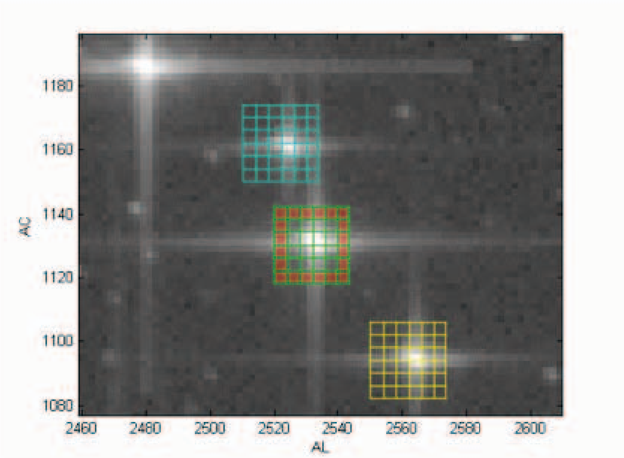
The focal plane assembly. Each of the 106 CCDs has its own front-end electronics (Proximity Electronic Module). The detection plane is made up of 7 rows. Each one is served for power, clock and data distribution by one Interconnection Module. The thermal dissipation is purely passive. The mass of the focal plane assembly is 190 kg and the power consumption is 430 W (Astrium SAS) of about one thousand million stars, requires a complex space and ground infrastructure. The expected accuracy of the order of 10 to 300 microarcseconds, depending on the magnitude and colour of the star, calls for extreme mechanical and thermal stability of the spacecraft.

The Payload Module is thermally insulated and its optical bench and nearly all optical elements are made of silicon carbide, a material which offers an extreme stiffness combined with a very low coefficient of thermal expansion. The spacecraft will be placed in a 'Lissajous' orbit around the Lagrange point L2, about 1.5 million km away from Earth in the anti-sunward direction. This location offers a highly thermally stable illumination by the Sun.

The Payload Module consists of two telescopes separated by a 'basic angle' of 106.5° sharing the same focal plane. The ultimate astrometric accuracy is determined by the size of the telescope aperture and the total number of photons detected. Therefore, fundamental design criteria are:
- mirrors M1 and M1' as large as possible but still compatible with the size of fairing of the Soyuz launcher;
- maximum transmittance of the optics and 'quantum efficiency' (i.e. the conversion efficiency of photons into electrons) of the CCD detectors; and
- large focal plane to simultaneously maximise signal integration time and number of stars detection.

Thanks to these specifications, Gaia will collect ten thousand times more photons in its five-year mission than the Hipparcos spacecraft did for a comparable star. Gaia will be able to see stars a thousand times fainter than Hipparcos, down to magnitude 20.

The detection of these photons is performed with CCDs, and the focal plane assembly consists of 106 CCDs and individual front-end electronics. The CCDs are arranged in seven rows, and the signals from each row are collected by



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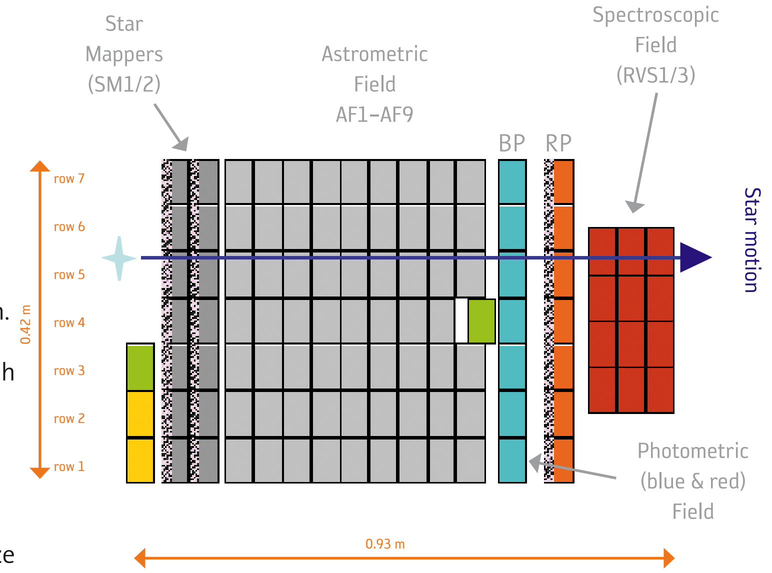
Simulation of a stellar field on the focal plane of Gaia and three 6x6 pixel windows assigned to detected stars. The content of the windows, after appropriate binning, is sent to the ground (Astrium SAS)



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The CCD focal plane. The strips SM1 and SM2 are used for inital star acquisition. The strips AF1 to AF9 constitute the astrometric field for precision position measurement. The strips BP and RP allow spectral measurement in the range 330–680 nm and 640–1000 nm. The strips RVS1 to RVS3 allow fine spectroscopy in the range 847-874 nm (Astrium SAS)

an Interconnection Module that handles power, data and clock distribution.

The very compact packaging of the electronics creates real challenges regarding heat rejection, integration and accessibility to the units during ground testing. Active thermal control with heat pipes is not an option due to mechanical noise introduced into the Payload Module.

The detection plane

Out of the 106 CCDs, 102 are dedicated to star detections and they are grouped into four fields: Star Mapper CCDs, Astrometric Field CCDs, Photometric Field (Blue and Red) CCDs and Spectroscopic Field CCDs (radial velocity measurement). A further four CCDs are used for monitoring the stability of the basic angle between the two telescopes and the quality of the optical performances.

As the two telescopes sweep the sky due to the spin of the spacecraft, the images of the stars in their respective field of view move across the focal plane. These images are seen first by the two strips of seven CCDs each, called Star Mappers. Each of the two strips is assigned to a telescope and detects star images only from that telescope.

Software classifies the signals detected by the Star Mappers either as stars (to be tracked in the following Astrometric Field) or as a 'transient' caused, for example, by a cosmic ray. In the latter case, the signal will be rejected. The software also allows a precise determination and control of the satellite's spin rate.

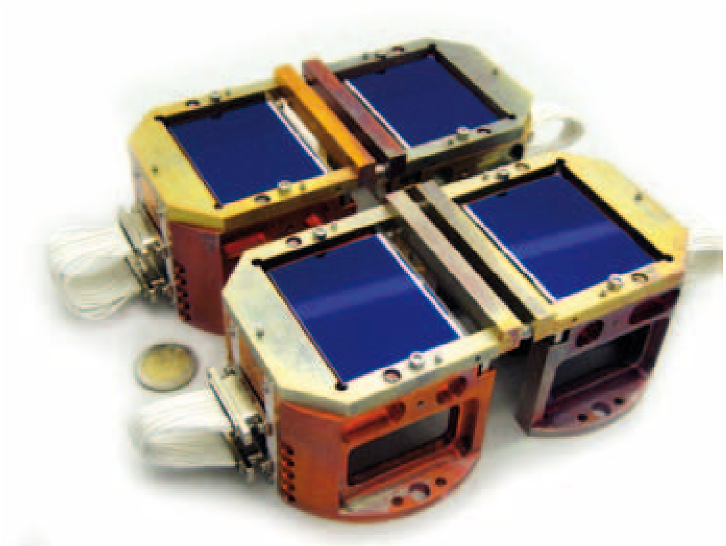
→

Basic detection and processing capabilities of the Gaia focal plane

Star design density for sizing of the focal-plane control electronics and scientific software resources	750 000 stars/deg²
Maximum number of simultaneous star detections which can be followed per CCD at any time	5400 stars
Maximum number of simultaneous star detections which can be processed by the CCD and control electronics per CCD per second	1200 stars
Maximum number of simultaneous star detections which can be followed in the astrometric focal plane at any time	334 000 stars
Maximum number of simultaneous star detections which can be processed by the focal plane per second	8400 stars

The confirmed star images will then sweep over the Astrometric Field where they are get assigned tracking 'windows'. Only the content of these 'windows' is transmitted to the ground. The windows are necessary to ensure that only useful information from each CCD is read out and treated by the subsequent star classification processes. The processing of each star image also requires a precise time-stamping by a rubidium atomic clock.

Next, the star images enter the Photometric Field where two low-resolution spectra are generated by dispersive optical elements. The first spectrum, the 'blue', is between 330 and 680 nm; the 'red' spectrum goes from 640 to 1000 nm. The spectra are dispersed over 45 pixels on the CCD and they are used for gathering colour information on the stars and correction of the chromatic aberrations in the astrometric part of the instrument.



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Four Astrometic Field (AF) CCDs mounted on their test jigs. The CCD is 45 x 59 mm with 8.8 megapixels. The associated field of view is 4.4 x 5.8 arcminutes. A star will take 4.42 seconds to cross the CCD (e2V technologies)

Finally, the star images enter the Spectroscopic Field where a spectrograph only allows light in the narrow band of 847–874 nm. The filtered light is then dispersed over 1100 pixels to detect characteristic spectral lines in the band. This allows, later on ground, the measurement of the red or blue shifts of the lines and the calculation of the stellar velocities in the radial (line-of-sight) direction. This part of the payload is called the Radial Velocity Spectrometer.

One of the enabling technologies to reach the required Gaia measurement accuracy is a long signal integration time and the detection of a large number of stars at the same time. This led to a focal plane of almost half a square metre, and hence the large-sized CCDs.

CCD operating modes and geometric characteristics

The optical image of a star on the Gaia focal plane, the Point Spread Function (PSF), corresponds to a 'charge cloud' that extends over a few pixels on a CCD. Unlike a normal digital camera that takes pictures as a full frame, the Gaia 'camera' tracks the movement of a PSF across the CCDs. In short, not one single image of a star is taken but a continuous sampling of the image is made as it moves across the focal plane.

The CCDs operate in a 'Time Delayed Integration' (TDI) mode, where the photoelectrons generated by the star image are clocked across a CCD together with the moving star image. The amount of collected charge at the output of the CCD is proportional to the brightness of the star image and the time it needs to cross a detector. A star similar to our Sun, with a magnitude of 15, accumulates a total charge of about 90 000 electrons during the crossing of a CCD. The moving star image, i.e. at the spin rate of the satellite, has to match the clocking speed of the charge cloud across the focal plane. To this end the Gaia spacecraft is equipped with a novel 'cold gas' micropropulsion system.

The relation between the size of the PSF and the size of the pixel of the CCD is fundamental for achieving the measurement accuracy. The focal length determines the size of the PSF on the CCD. It has to be long enough and the pixel small enough such that the PSF can be sampled with a sufficient number of pixels. On the other hand, the pixel must be large enough to avoid images of brighter stars to cause a local saturation on the CCD. The best compromise was found with a 35 m focal length and pixel sizes of 10 µm along the star-crossing direction and 30 µm perpendicular to it. The charge handling capacity of each pixel is about 190 000 electrons.

The objects observed will vary enormously in terms of brightness and size. The number of charges generated can vary from above a few million electrons for bright stars down to few electrons per pixels once spectrally dispersed in the spectroscopic field. Because at any given time there is a combination of faint and bright stars images on the focal plane, each CCD must be able to handle saturated pixels and allow modulation of the integration time. This leads to the implementation of an 'anti-blooming' function and 'gates' to adapt the integration time to the brightness of the star.

Furthermore, the readout register and output amplifier need to be capable of operating at very different frequencies. For example, the Star Mapper CCDs have to process all presumed star images in order to quickly select the correct ones for further monitoring in the subsequent fields. Astrometric Field CCDs deal with an already selected set of images and Spectrometer CCDs see a further reduction in useful signals. Thus, operating frequencies of the CCDs vary from a few tens of kilohertz for the spectroscopic field to about a megahertz for the Star Mappers. One of the outstanding features of the Gaia CCDs is an average noise level of less than six electrons in the output amplifier.

The physical size of the CCDs has been chosen to match today's wafer technologies (5-inch/127 mm wafers) and to be in line with realistic production yields of the manufacturing company. The Gaia CCD features 4500 pixels in the along-scan direction and 1966 pixels in across-scan. The packaging of the CCDs is selected for maximum packing density and best thermomechanical properties, since the focal plane operates at about -110°C.

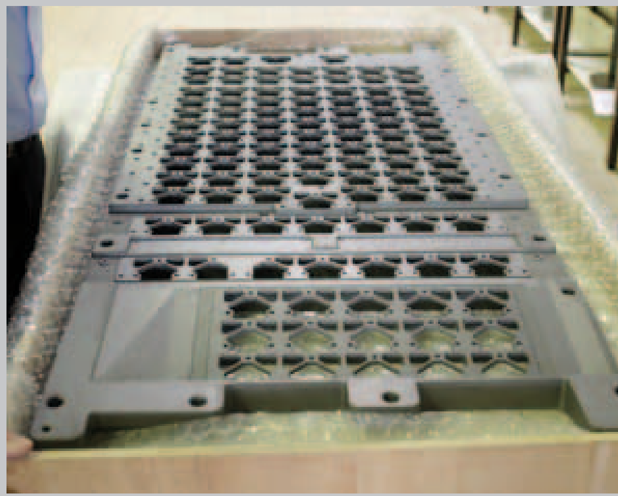
Radiation effects and implications for performance

In space, the CCDs will be subjected to irradiation by energetic particles that have an impact on the long-term behaviour of these detectors. In particular, solar and cosmic background radiation generates defects in the detector crystal lattice, which can trap electrons and release them later. This effect is not good for the science of Gaia, since it changes the shape of the PSF of a star image and interferes with the highly accurate determination of the maximum value of the PSF. The radiation causes the following effects:

- Charge loss in the PSF of typically 20% at the radiation dose accumulated at the end of the Gaia mission. This affects the astrometric, photometric and spectroscopic measurements as all three depend on the number of collected photoelectrons.

- Bias of the uncorrected star position measurement of typically 0.16 pixels (10 milliarcseconds) at the end-of-life radiation dose. This is a consequence of electron trapping and delayed release. This affects astrometry, photometry and spectroscopy by shifting the spectral lines and mixing up wavelengths.

- Release of trapped electrons could happen while subsequent star images transit the releasing traps. Electrons would be added to the PSF, which is comparable with the effect of stray light in the telescope.



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The Gaia CCD Support Structure. The structure is made by sintered silicon carbide which guarantees an extreme thermal and mechanical stability (Boostec Industries)

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CCDs manufactured for the Gaia development and flight programme

	Astrometric CCDs	Blue-enhanced CCDs	Red-enhanced CCDs
Breadboard models	11	1	1
Engineering models	20	3	8
Flight models and spares	94	10	26

Evaluation testing	Constructional analysis	Environmental /mechanical	Assembly /capability	Endurance	DPA
Astrometric CCDs	2	10	Performed as part of the DPA	12	2
Blue-enhanced CCDs	1	4 for irradiation. Vibration/shock testing and temperature cycling evaluated by similarity with astrometric CCD	Performed as part of the DPA	3	1
Red-enhanced CCDs	1	4 for irradiation. Vibration/shock testing and temperature cycling evaluated by similarity with astrometric CCD	Performed as part of the DPA	3	1

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Summary of CCDs allocated for project evaluation tests, with a total of 40 devices used (DPA = destructive physical analysis)

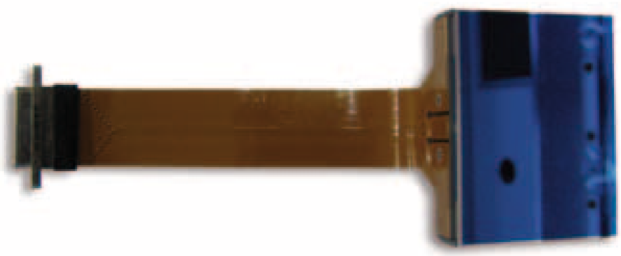
Shortly after the start of the overall spacecraft development programme in 2006, a systematic test campaign was initiated with irradiated CCDs. These tests are still ongoing at Astrium SAS. The tests, as well as the analysis of intermediate results, were carried out to: understand the radiation bias process; provide a quantitative assessment of its effect on astrometry, photometry and spectroscopy; investigate the benefit of electronic charge injection and other mitigation possibilities; and derive an algorithm to systematically correct the data stream for the radiation effects.

The ongoing tests are also used for the detailed theoretical modelling of the radiation effects, and will consolidate the strategy for removing the radiation effects from the scientific measurements. Given the criticality of the issue for the Gaia mission, the test campaign is conducted in close cooperation between the industrial prime contractor, the ESA project team and the scientific community.

Manufacturing, performance testing and qualification testing

All CCDs populating the focal plane have the same format and, in principle, the same function. Some differences exist due to the wavelength range for which they are optimised. Three different CCD types were developed: the astrometric, the 'red-enhanced' and the 'blue-enhanced'.

The only difference between the astrometric CCD and the 'blue' CCD is the additional anti-reflection coating optimised for maximum quantum efficiency at the chosen wavelength. The 'red' CCDs are manufactured from high-resistivity silicon. The thickness of this detector is 40 µm for enhanced quantum efficiency instead of the 16 µm used for the other two CCD types.



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Gaia's photometric and spectrometric CCDs: top, the red photometer and, below, the blue photometer. These CCDs are variations of the astrometric CCD to enhance perform-ances in the blue and red parts of the optical spectrum. The red CCD is blue in colour because it absorbs red light and reflects blue (e2V technologies)

QLAT testing	Environmental /mechanical	Endurance	DPA
Astrometric CCDs	2 every 10 manufacturing batches for the vibration/shock testing and temperature cycling. 1 per batch for irradiation	2 per 10 FM manufacturing batches	1 device per 10 FM manufacturing batches
Blue-enhanced CCDs	2 every 3 manufacturing batches for the vibration/shock testing and temperature cycling. 1 per batch for irradiation	2 per 3 FM manufacturing batches	1 per 3 FM manufacturing batches
Red-enhanced CCDs	2 every 3 manufacturing batches for the vibration/shock testing and temperature cycling. 1 per batch for irradiation	2 per 3 FM manufacturing batches	1 per 3 FM manufacturing batches

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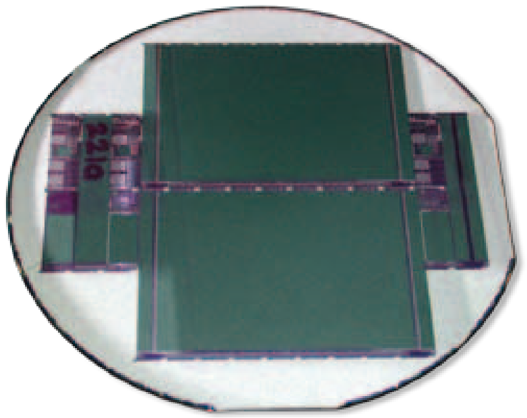
Summary of CCDs allocated for the Qualification and Lot Acceptance Test (QLAT), with a total 20 used (FM = flight model quality)

The quantities needed by the project are unusual for a space programme, and a total of 174 CCDs is being manufactured. The CCD qualification and lot acceptance testing programme followed ESA's standard process but some tailoring was applied for specific needs. The Gaia CCD, named CCD91-72, was custom designed for Gaia mission and thus a thorough evaluation testing programme had to be implemented prior to the qualification and lot acceptance testing.

The total number of devices required for the evaluation testing would have been more than 300, which would have far exceeded the available time and finances. So before the start of the spacecraft development programme, and in close cooperation with the manufacturer e2v technologies, the project reassessed the qualification needs for the CCD91-72 and established a method which ensured that the build standard would be maintained and controlled over a manufacturing period of a few years. Eventually, a total of 40 CCDs have been used for evaluation and distributed over the classical test branches.



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Two CCDs are 'printed' on the sample silicon wafer. The small CCDs on either side are used for the radiation test during the Lot Acceptance Tests

Particular attention was paid to the flexible cable connecting the CCD with the front-end electronics, because a new attachment technique was required. This process underwent a thorough constructional analysis and out-gassing test and was completed with cold-temperature pull tests to verify its mounting to the CCD package.

For radiation testing, the logic of having one CCD tested per flight model batch would have been very time and money consuming. It was therefore agreed to incorporate two small dedicated 'radiation test CCDs' on each wafer. Thus, the Gaia wafers contain two CCD91-72 and two CCD221 dices.

Large-scale production and schedule

The number of CCDs to be manufactured for Gaia is impressive: 174 CCDs need to be delivered for focal plane development and flight model integration; another 60 are necessary for the evaluation and qualification programmes, totalling 234 devices. This large-scale production of space-qualified devices was new and presented a challenge for e2v technologies.

Note though that the production of semiconductor devices always has a yield rate. This means that, due to imperfections in the production flow, several devices might need to be rejected before a good device can be accepted. The yield rate is kept confidential by the manufacturer but it can be as low as 10%, i.e. ten devices have to be produced to have one of acceptable quality. So the total number of Gaia CCDs produced at wafer level may well be around 2000!

Late in 2004, discussions with e2v technologies established that the manufacturing, qualification, and delivery of all FM CCDs would take about 3.5 years. This was considered too long and not compatible with the nominal planning for the development of the spacecraft. Therefore, the Gaia project concluded that a go-ahead for the CCD production needed to be given before selection of the Gaia industrial prime contractor. So ESA placed a contract for the procurement of the CCDs nine months before the release of the Gaia ITT for the development phase of the spacecraft.

However, an early start alone was not sufficient to fully secure the schedule. A detailed analysis of the testing approach and time needed for it was also performed. At that time, the Gaia CCD was already subject to three years of pre-development during which 20 devices were manufactured and tested. The overall test time per CCD was about 31 hours. Each CCD required more than 18 electrical and electro-optical parameters to be measured, without counting all the wavelengths requested for establishing the quantum efficiency and modulation transfer function curves.

Most of these tests had to be made at the operating temperature of -110 °C in dedicated cryostats. During the technology development phase, only one test bench was available. This was later increased to five benches fully dedicated to Gaia. Today, the total time taken for the testing per CCD is about 18 hours. Therefore, the original testing capability at e2v technologies has been increased by a factor five and the testing time per CCD has been reduced by almost a factor two.

To date, more than half of the flight CCDs have been delivered well in advance of the dates needed, including all engineering models and most of the astrometric and 'blue' type flight models.

Acknowledgements & further reading

The authors thank all people and organisations who made this challenging development and production possible: the e2v technologies team, the CCD/focal plane team at Astrium SAS, the ESA TEC-MME and TEC-QCT teams and involved scientific groups.

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