ESA'S GAIA MISSION:
a billion stars with a billion pixels

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Astrometry is the astronomical discipline of measuring the positions, and changes therein, of celestial bodies. Accurate astrometry from the ground is limited by the blurring effects induced by the Earth's atmosphere. Since decades, Europe has been at the forefront of making astrometric measurements from space. The European Space Agency (ESA) launched the first satellite dedicated to astrometry, named Hipparcos, in 1989, culminating in the release of the Hipparcos Catalogue containing astrometric data for 117 955 stars in 1997. Since mid 2014, Hipparcos' successor, Gaia, has been collecting astrometric data, with a 100 times improved precision, for 10 000 times as many stars.

Although astrometry sounds boring, it is of fundamental importance to many branches of astronomy and astrophysics. The reason for this is that astrometry can determine direct, that is model-independent, estimates of stellar distances and velocities through the measurement of parallax – the periodic, apparent displacement of a star on the sky as a result of the changing position of the observer as the Earth revolves around the sun – and of proper motion – the continuous, true displacement of a star on the sky as a result of its velocity in space relative to the sun. Measuring the distances to (and motions of) stars has been a central theme for hundreds and even thousands of years, primarily driven by the human urge to understand the cosmos and the place of the earth (and the heavenly bodies). Despite huge efforts, and even with the invention of the telescope in 1608, the first reliable parallax measurement of a star other than the sun was only made in 1838. The reason for this late success is the fact that stars are located at extremely large distances such that parallaxes are typically tiny, of the order of (fractions of) milli-arcseconds (there are 60 arcseconds in an arcminute, 60 arcminutes in a degree, and 360 degrees in a circle). ESA's Gaia mission, however, has made an industry of measuring parallaxes and proper motions, by collecting vast amounts of astrometric data – and also photometric and spectroscopic data – for more than 1000 million stars with micro-arcsecond precision [1].

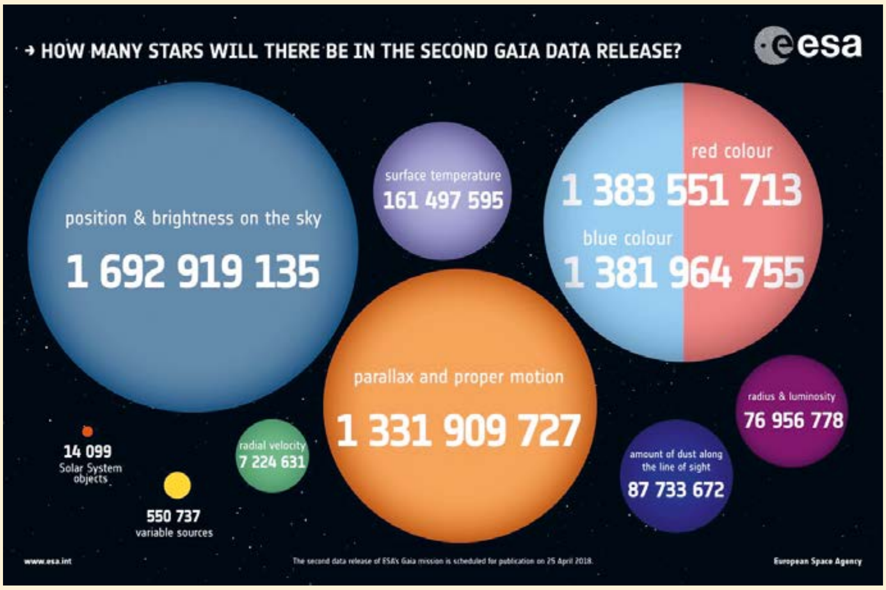

Figure 1. Schematic overview of the contents of Gaia DR2, released on 25 April 2018. Original: http://sci.esa.int/gaia/60147-waiting-for-gaia-s-second-data-release/

The Gaia mission

Launched in December 2013, Gaia has been scanning the sky since mid 2014 without interruption. The science data collected by Gaia is being converted to useable format, *i.e.*, to star catalogues, by the pan-European, mostly nationally-funded Gaia Data Processing and Analysis Consortium (DPAC). DPAC combines the astronomical and information technology knowledge of more than 400 individuals, spread over dozens of mostly academic institutes throughout Europe. Before

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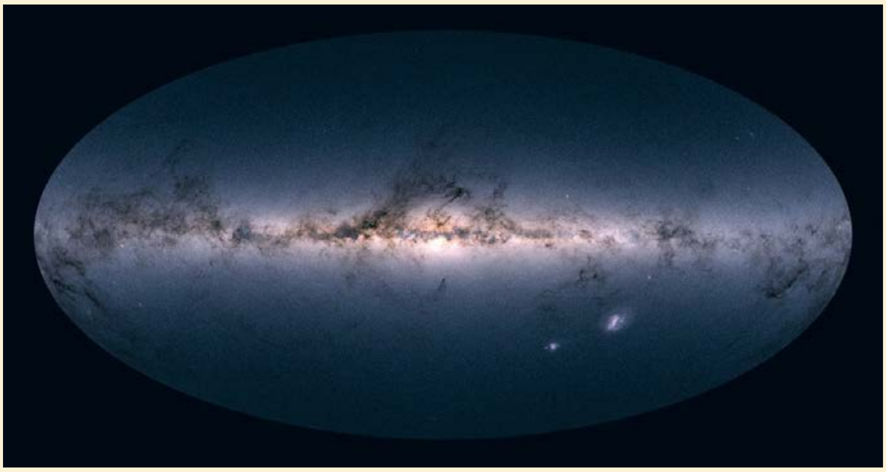

Figure 2. Gaia's all-sky map in colour, based on the Gaia DR2 catalogue. Original: https://www.esa.int/spaceinimages/Images/2018/04/Gaia_s_sky_in_colour2

being released, the Gaia data are being processed in six data processing centres (Madrid, Barcelona, Toulouse, Cambridge, Genève, and Turin).

So far, ESA and DPAC have made two intermediate data releases, Gaia DR1 in September 2016 and Gaia DR2 in April 2018 (*Figs. 1* and *2*; [2]). With unlimited excitement, astronomers have been sifting through the data to enable them to claim breakthrough discoveries such as the discovery of velocity structures in the disk of the Milky Way caused by the fairly recent infall of a satellite galaxy, the discovery of crystallisation of degenerate matter inside the cores of white dwarf stars, and the discovery of a cannibalistic event some 10 billion years ago in which our Milky Way, in its younger years, devoured an innocent, smaller galaxy – named Gaia-Enceladus – that happened to be passing by. Obviously, these discoveries reflect the unique contents and unique quality of the data. These, in turn, reflect the unique design of the Gaia telescopes and instruments.

Gaia satellite and payload

Gaia's implementation phase started in 2006, with EADS Astrium, nowadays Airbus Defence & Space, in Toulouse as prime contractor. The Gaia satellite consists of two parts: the service module and the payload module (*Fig. 3*). Two large telescopes with rectangular apertures are installed on a stable ceramic support structure called the torus. The lines of sight of the two telescopes are ultra-stable and form

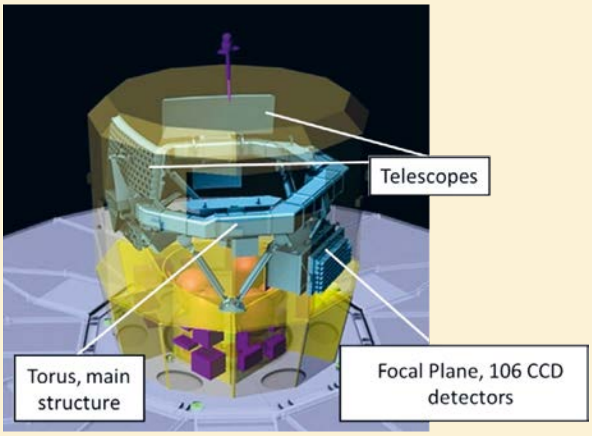

Figure 3. Gaia satellite and payload schematic. Image courtesy Airbus Defence & Space.

the so-called basic angle of 106.5°. The images of the two telescopes are projected on the largest focal plane operated in space [3]. Some 106 Charge Coupled Device (CCD) sensors are assembled in the focal-plane assembly, containing 938 million pixels. Sixty-two sensors are devoted to the main objective, collecting astrometric data, using the broadest possible band pass (330-1050 nm). The function of the remaining sensors is described below.

The satellite rotates once every six hours, with the rotation axis slowly precessing around the solar direction to achieve full sky coverage every few months. Due to the six-hour rotation, stars seen by the two telescopes are travelling slowly across the focal plane. A star crosses a single CCD sensor during 4.4 seconds. During this time, the charges released in the silicon by the photons impinging on the detector are shifted electronically, with atomic-clock precision, with exactly the same speed as the optical images move over the detector surface. At the output of each CCD row, all charges generated by a star travelling across the focal plane are collected, before being digitized and transmitted to ground for science analysis. Since stars from both telescopes are measured in the same focal plane, the angular distance of any pair of stars originating from different telescopes can be measured with extreme precision. Considering that the basic angle between the two telescopes is stable, the angular distance between the two stars can be measured with the required micro-arcsecond precision.

Gaia optics

The Gaia optics consist of two main, identical telescopes, two optical instruments (Radial Velocity Spectrometer – RVS; Blue and Red Photometers – RP/BP), and three optical sensors (Basic Angle Monitor – BAM; Wave Front Sensor – WFS; Star Mapper – SM). The two telescopes are off-axis Three-Mirror-Anastigmat (TMA) designs of the type concave-convex-concave with an intermediate image between the secondary and tertiary mirrors (*Fig. 4*). Three more flat folding mirrors, shared by both telescopes, bring the photons to the focal plane. The rectangular aperture size of the telescopes is 1.45×0.50 m^2; the focal length is 35 m. Such a telescope is challenging to build and align but TMAs have excellent image quality and an enormously large field of view. Each telescope has a field of view of 1.8°×0.7° and achieves diffraction-limited image performance in the visible wavelength range (330-1050 nm).

All mirrors, as well as the main Gaia payload structure, are made of silicon carbide (SiC). This ceramic material provides the extreme payload stability that is required for the science objectives of the mission. In order to minimise the mirror masses, the mirror blanks have been light-weighted by a pattern consisting of triangular cells (*Fig. 5*). Each primary mirror weighs about 40 kg.

Twelve of the 106 CCD sensors in the focal plane are dedicated to the Radial Velocity Spectrometer (RVS). This instrument mainly measures the radial velocity of an observed object, that is the velocity along the line of sight from the observer to the star, by Doppler shifts of absorption lines in the spectral range between 845 and 872 nm. Optically, the RVS consists of a band pass filter plate, a number of prisms, and a transmission grating. Two of the four prisms employ curved optical surfaces for optical correction. Such prisms are called “Féry prisms” and are challenging to manufacture. The spectrometer is installed close to Gaia’s focal plane and is an integral-field unit: since stars are basically point sources, neither a spectrometer slit nor extra spatial masking is required.

The Gaia photometric instrument consists of two prisms (a Blue Photometer named BP and a Red Photometer named RP) that are part

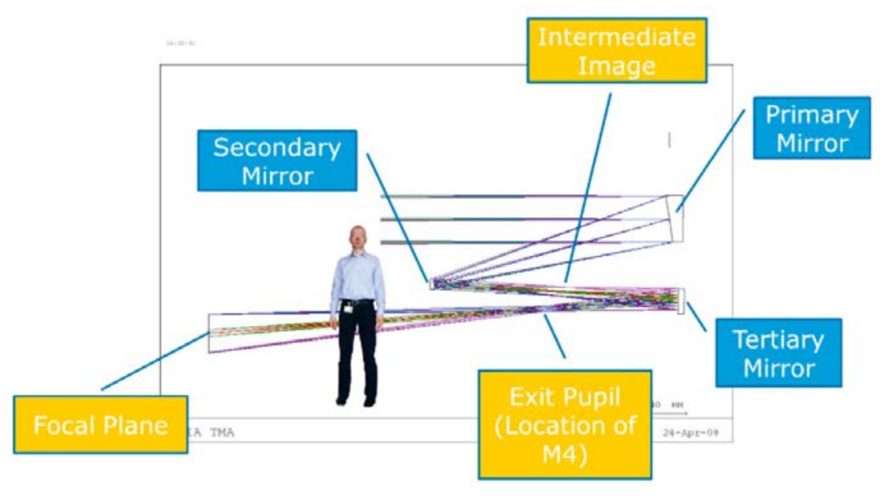

Figure 4. Gaia TMA telescope design with one of the authors depicted for scale. Image courtesy Airbus Defence & Space and M. Erdmann.

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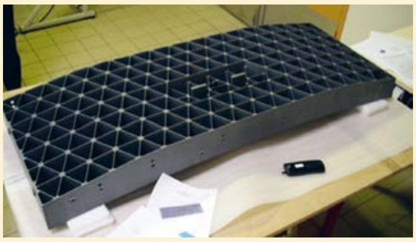
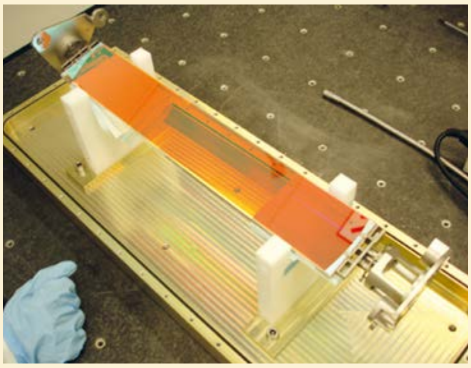


▴ **Figure 5.** Gaia primary-mirror blank. Image courtesy Airbus Defence & Space.



▸ **Figure 6.** Gaia red photometer prism. Image courtesy Airbus Defence & Space.

of the focal plane assembly (*Fig. 6*). Each prism has a selective band pass filter, implemented through a coating, that allows a limited spectral range in the blue (330-680 nm) or red (640-1050 nm) to pass through the prism and to reach the focal plane. The two prisms form low-dispersion spectrometers and the colours of stars, as well as more sophisticated astrophysical properties such as their surface temperature and gravity, can be derived from the two recorded low-resolution spectra. Fourteen of the 106 CCD detectors are dedicated to the photometric instrument.

The Basic Angle Monitor (BAM) is one of the key optical sensors of the Gaia payload [4]. The two lines of sight of the two telescopes of the Gaia payload are separated by 106.5°. This angle (the "basic angle") is the reference for all astrometric measurements. Its variation over the six-hour rotation period of the spacecraft must be known at sub-micro-arcsecond levels. The BAM therefore continuously measures variations in the basic angle by injecting two optical laser beams into each of the two telescopes. These beams have a diameter of about 1 cm and are separated by 600 mm in the rotation plane of the satellite. The optical configuration of the BAM represents a Young's interferometer. For each telescope, the two beams interfere, forming Young's fringes that are observed in the CCD sensor. Any variation in the basic angle results in a relative yet measurable shift of the fringe patterns produced by both telescopes and that are imaged in the same sensor in the focal plane. In the scientific data processing on ground, the astrometric star positions are corrected according to the BAM readings. Two of the CCD sensors are used as BAM sensor, one nominal and one redundant. In case of a laser source failure, a redundant source can be activated. The nominal and redundant sources are separated such that they end up at one of the two BAM sensors in the focal plane. The BAM detectors are the two extreme left detectors in *Figure 7*.

Two wave front sensors (WFS) are installed directly on the focal plane of Gaia. Each WFS is of Shack-Hartmann type. Each sensor consists of an optical mirror that images both telescope entrance pupils on a dedicated CCD sensor in the focal plane. Each telescope pupil image is segmented into 3×9 sub-pupils by the WFS optics. The two WFS measure the actual Gaia telescope wave front errors in orbit through observation of (bright) stars (*Fig. 8*). Each of the two telescopes contains a high-precision actuator that can move their secondary mirror in five degrees of freedom, with only a rotation around the optical axis not being supported. Since the telescope alignment was done on ground, under 1 g conditions, it was significantly influenced by gravitational forces acting on the whole payload. Gravity forces were considered during alignment insofar possible, but a vanishing remain of unpredictable unknowns could not be taken into account. In order to achieve the required optical performance, it was necessary to measure the actual wave fronts of both telescopes in orbit and to improve them as needed by a slight movement of the secondary mirrors. This has been done once during the commissioning phase [5], after thermal equilibrium of the payload was reached, and several times during nominal operations, mainly to refocus the optics after thermal decontamination of the payload.

For the angular measurement precision of Gaia, it is paramount to have the images of both telescopes superimposed on the same focal plane. However, for the proper scientific evaluation of the images on ground, as well as for the on-board software that governs the read out of the CCD detectors, it is important to know which of the two telescopes a given star originates from. Two columns of 7 CCD sensors each are used for this purpose. Together with two masking

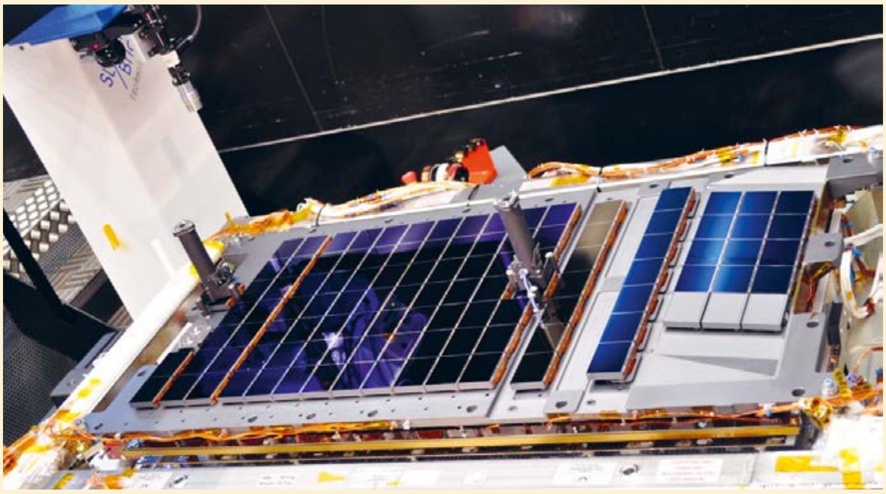


Figure 7. Gaia focal-plane assembly consisting of 106 CCD detectors. The two Wave Front Sensors are the booms sticking out vertically in the middle and at the left edge. The 3×4 block of CCDs on the right belongs to the RVS. Image courtesy Airbus Defence & Space.

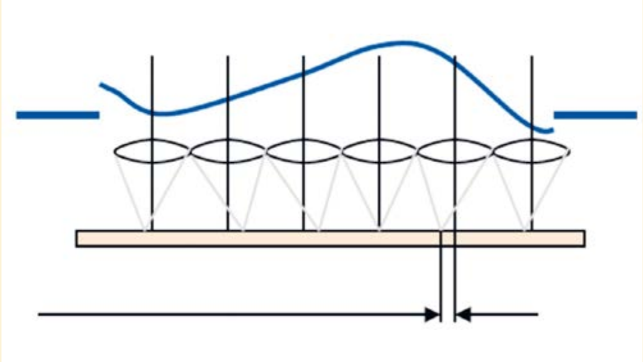


Figure 8. Principle of the Shack-Hartmann wave front sensor. The measurable distance between the two arrows is proportional to the local slope of the wave front error.

elements in the telescope optics, each effective for only one of the telescopes, they form the Star Mapper. The 14 Star Mapper sensors are shown on the left side, next to the two BAM CCDs, in *Figure 7*.

Conclusion

ESA's Gaia mission, with its custom optical design and high-quality instruments and metrology sensors, is revolutionising astronomy through the measurements of the distances and motions, as well as intensities and colours, of more than 1000 million stars. The two data releases made so far have led to hundreds of exciting discoveries, varying from stars zipping by the Sun in the recent past to a major collision that helped shaping our Milky Way galaxy some 10 billion years ago. At least two more data releases are being planned and a mission extension of 1.5 years on top of the nominal, five-year mission has been approved. Propellant on board would allow extending the mission to late 2024, which would allow improving the quality of the science data products to levels such that they will remain an astronomical treasure trove for decades to come. ■

FURTHER READING

[1] Gaia Collaboration, The Gaia Mission. *Astronomy and Astrophysics*, 595, A1 (2016)

[2] Gaia Collaboration, Gaia Data Release 2. Summary of the contents and survey properties. *Astronomy and Astrophysics*, 616, A1 (2018)

[3] de Bruijne, J.H.J.; Kohley, R.; Prusti, T., *Gaia: 1000 million stars with 100 CCD detectors. Proceedings Volume* 7731, Space Telescopes and Instrumentation 2010: Optical, Infrared, and Millimeter Wave; 77311C (2010)

[4] Gielesen, W.; de Bruijn, D.; van den Dool, T.; Kamphues, F.; Meijer, E.; Braam, B.C., Gaia Basic Angle Monitoring system, *Proceedings Volume* 10564, International Conference on Space Optics — ICSO 2012; 105641Z (2017)

[5] Mora, A.; Biermann, M.; Bombrun, A.; Boyadjian, J.; Chassat, F.; Corberand, P.; Davidson, M.; Doyle, D.; Escolar, D.; Gielesen, W.L.M.; Guilpain, T.; Hernandez, J.; Kirschner, V.; Klioner, S.A.; Koeck, C.; Laine, B.; Lindegren, L.; Serpell, E.; Tatry, P.; Thoral, P., Gaia: focus, straylight and basic angle, *Proceedings Volume* 9904, Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave; 99042D (2016)

https://doi.org/10.1051/photon/2019S438