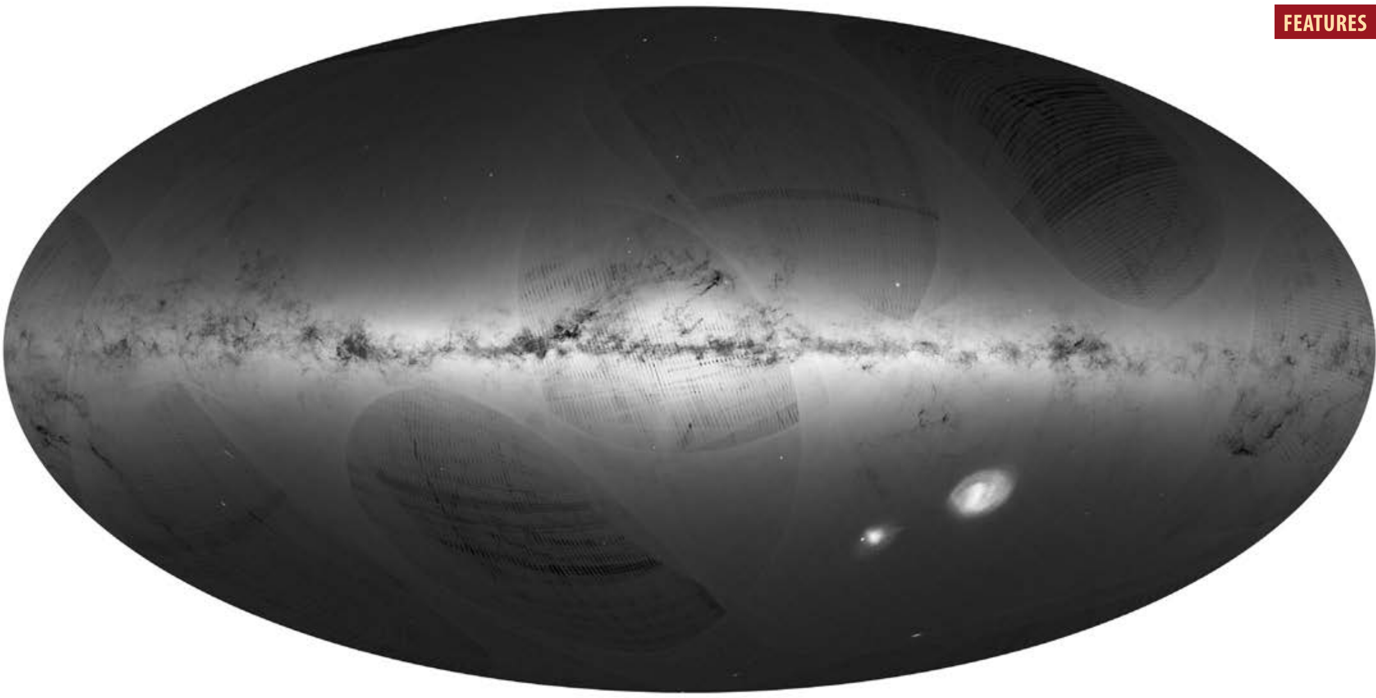


GAIA: SCIENCE WITH 1 BILLION OBJECTS IN THREE DIMENSIONS

Timo Prusti – European Space Agency (ESA) and ESTEC – Noordwijk – The Netherlands – DOI: https://doi.org/10.1051/epn/2018103

Gaia is an operational satellite in the ESA science programme. It is gathering data for more than a billion objects. Gaia measures positions and motions of stars in our Milky Way Galaxy, but captures many asteroids and extragalactic sources as well. The first data release has already been made and exploitation by the world-wide scientific community is underway. Further data releases will be made with further increasing accuracy. Gaia is well underway to provide its promised set of fundamental astronomical data.

Gaia is a cornerstone mission in the science programme of the European Space Agency (ESA). The fundamental scientific goal of Gaia is to reveal the structure and formation of our Milky Way Galaxy. This is achieved by measuring the position and motion of more than 1 billion stars. It is building on the heritage of its predecessor Hipparcos, an ESA mission that mapped the positions, distances and motions of more than 100,000 stars in the Solar neighbourhood. With respect to Hipparcos, Gaia improves thus in number of objects, but even more so in accuracy. Furthermore, Gaia is doing not only astrometry, measuring positions and motions, but provides also photometry and spectroscopy. While measuring the positions over the operational 5 year period it is possible to deduce the motion on the plane of the sky, but for the radial velocity component spectroscopy, based on the Doppler effect, is required. Therefore the title of the article is in fact too humble: Gaia provides data in 6 dimensions. Furthermore the photometry and spectroscopy can be used to deduce astrophysical properties of the stars detected by the satellite. By knowing temperature and brightness of stars, astronomers can get a hold on ages and masses, which are essential to understand the formation and evolution of the Milky Way.

While stars are the primary targets of Gaia, the mission will make a major contribution to solar-system and extragalactic studies as well. This is thanks to the observing strategy of Gaia. The satellite has no knowledge of the sky in advance. It has a detection system on-board based on magnitude threshold and gathers data of any bright enough point source. Although the majority of objects are stars most asteroids and many galaxies look also point-like to Gaia and observations are made. The precise position measurements of asteroids allow determination of the orbital elements to higher accuracy than is possible from ground-based measurements. This, combined with taxonomic information from photometry, allows more detailed studies between relations of orbital families of small bodies in the solar system and their physical characteristics. With extragalactic sources it is possible to provide fundamental

▲ The first Gaia all-sky view based on star counts. Brighter areas on the map means higher concentration of stars. Credit ESA/Gaia/DPAC relations between radio and optical reference systems. This is important because a large number of quasars used to define the reference frame based on radio observations are also visible to Gaia. The overarching aim of the Gaia mission is to contribute to fundamental astronomy across many scientific disciplines.

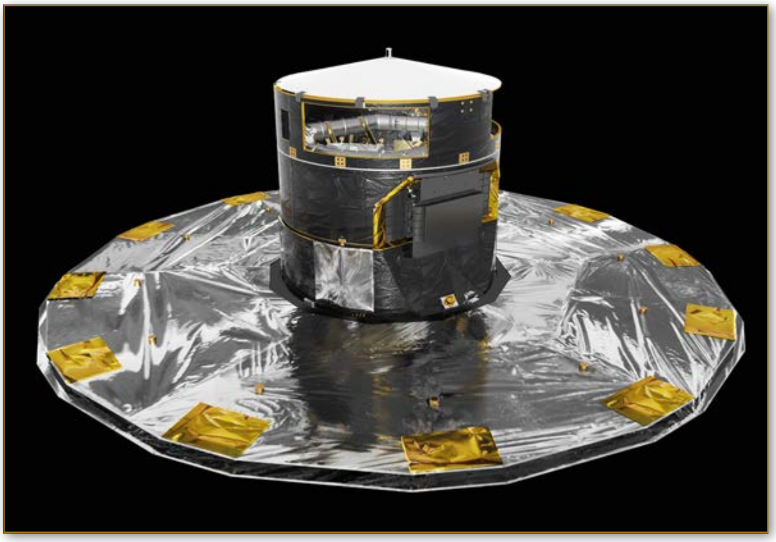
Spacecraft

The Gaia satellite was built by Astrium, Toulouse (now 'Airbus Defence and Space') as the prime industrial contractor. Unlike most ESA science missions, which have scientific instruments built in institutes in member states, in Gaia the payload was constructed by the prime industrial partner too. This was done due to the system approach needed to ensure stability across the satellite. The design driver in Gaia was the extreme stability needed to achieve the high accuracy required for astrometry. Any and all thermal connections to and in the payload had to be understood and minimised. Additionally, during science operations there are no moving parts in the satellite. An illustrative example of the level of detail required in design is read-out electronics. Reading out a small amount of data from the detector creates a small amount of heat. When scanning dense stellar fields there are more objects thus creating more heat than in sparse fields. This is not acceptable and therefore Gaia does 'fake reading' in regions with less stars so that the amount of reading activity is always constant.

Gaia has many unique features in its design. First of all Gaia has two telescopes looking at two fields of view 106.5 degrees away from each others. These two views are required to be able to do absolute astrometry. The fields of view are projected on a single focal plane with 106 Charge Coupled Devices (CCDs). The CCDs are operated in a specific mode taking into account the fact that Gaia is constantly scanning the sky. The way to keep the images sharp is to move the charge *i.e.* to move the images on the CCDs at exactly the same speed as the satellite is spinning. Thus Gaia is making constantly a picture of the sky where the width is the width of the detector, but the length has no limitation as it simply continues along the scanning of the spacecraft. It would be wonderful to get this Hubble Space Telescope resolution image of the full sky back to the Earth for analysis, but there is no way to transmit all data down. Therefore Gaia sends data only of pixels which have bright enough point sources in them. This is the case not only for astrometry, but also for photometry and spectroscopy.

Photometry in Gaia is achieved with two prisms. The light of a star is simply spread along the scanning direction and recorded on dedicated photometry CCDs. Spectroscopy follows the same principle, but for high resolution it is necessary to guide the light through a specific optical assembly (Radial Velocity Spectrometer) before recording the data. While photometry is done to all objects for which astrometry is done, spectroscopy can only be done to some 150 million brightest objects.

▾ **FIG. 1:** Gaia spacecraft. © ESA



Operations

Gaia was launched 19 December 2013 from Kourou with a Soyuz rocket. The travel time to its operational point, L2 (the second Lagrange point in the Sun-Earth system), took about a month. The commissioning period was successfully completed in half a year and since summer 2014 Gaia has been performing its routine science programme. An orbit around L2, which is beyond the Earth, was chosen for operations as there Gaia can turn its shield to hide not only to the Sun, but also toward the Earth and the Moon. The telescopes thus always look at the dark sky.

As already mentioned Gaia is constantly scanning the sky. However, the requirement is to cover the full sky as homogeneously as possibly. Furthermore, every point of the sky should be scanned with differing scanning angles to prevent any systematic effects creeping into the measurements. The scanning law followed by Gaia is a compromise between technical and scientific requirements. A technical requirement, for example, is that for thermal reasons the spin axis of Gaia is always precisely 45 degrees to the Sun. With this constraint the homogeneity of scanning is best achieved by combining the scanning with a slow precession of the spin axis of the spacecraft to the natural movement of L2, and Gaia thereby, around the Sun in a year.

Despite on-board processing done in Gaia, the amount of data transmitted to the Earth is enormous. Three ESA ground stations in Spain, Australia and Argentina are used to get the data down. When the scanning direction is along the Galactic plane, Gaia is producing so much data that essentially full time coverage is needed (and even then not everything can be sent); normally less than 10 hours per day is required for the downlink. Now more than three years in operations Gaia is truly in routine phase. Gaia is occasionally disturbed by micro-meteoroids, but it recovers autonomously typically in few minutes. All in all an amazing 10^{12} measurements have been collected so far.

Data processing

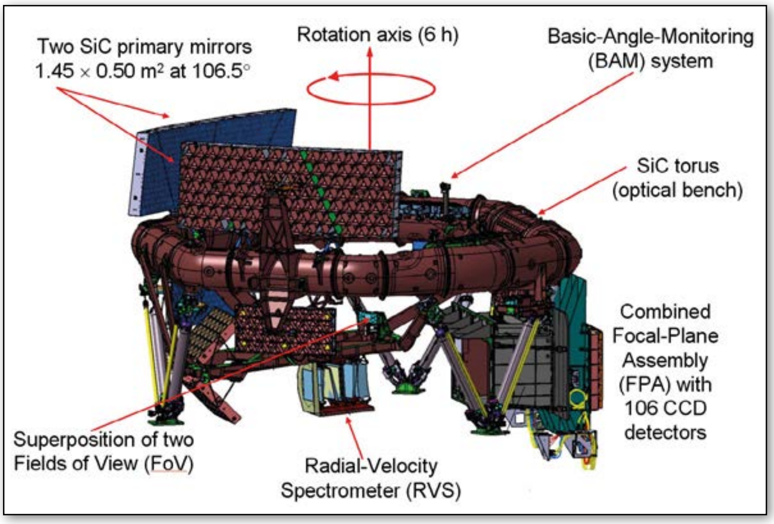
The huge amount of data collected by the spacecraft requires a major data processing effort. For Gaia, Data Processing and Analysis Consortium (DPAC) was chosen for the task. DPAC has about 500 members, scientist and engineers, working full or part time in research institutes and universities all over Europe. The consortium brings together experts of specific scientific topics working in a structure of coordination units producing code running in six data processing centres. While it is necessary to combine the expertise residing across institutes in Europe, the distributed data processing approach poses also challenges. A lot of attention had to be spent on ensuring good information flow throughout the consortium so that integration of the algorithms led to working code in data processing. After several years of preparations the pipelines needed still a major revision as the true data always have features not anticipated. Nevertheless, DPAC managed the challenge and the first data release (Gaia DR1) was achieved in September 2016.

Gaia DR1 is considered to be a taster for what is to come. That may be too humble a statement. Gaia DR1 increased the number of trigonometric distance measurements from 100,000 to above 2 million. In comparison to the 1 billion to come this is a small number, but a huge step in comparison to Hipparcos. Additionally Gaia DR1 contained position and brightness for more than 1 billion sources. The most accurate sky map produced ever. For about 3,000 variable stars also the light curves of the first year of observations were produced. Purely from operational perspective Gaia DR1 was an excellent training for future releases, but also scientifically the data have been used extensively.

Science results

Since Gaia DR1 some 250 refereed articles using Gaia data have been published. Although the distances estimates are not yet good for sources far away, the data set allowed to look further and more precisely in the Solar neighbourhood. Many marginal Hipparcos results were addressed and controversies were resolved. Also new questions were raised. In recent years asteroseismology has made major progress and Gaia DR1 allowed to test the results. First it appeared that distances between asteroseismological work and Gaia do not match, but later studies indicated much less discrepancy. This is clearly a topic that will be extensively addressed in future Gaia releases where the errors in distances will become significantly smaller.

Gaia DR1 has been used often in combination with ground-based data from spectroscopic surveys. Addressing the interplay of Milky Way stellar components is best done when the position and motion information is combined with the knowledge of astrophysical properties of stars based on spectroscopic analysis. In future releases this area of Milky Way research will receive a huge boost with the increased number of stars observed by Gaia with small errors.



▲ **FIG. 2:** Gaia Payload Module. ©ESA

Gaia DR1 also allowed to conduct the first comparison of quasar positions in radio and optical wavelengths. Quasars are known to have jets and purely from astrophysical perspective it is possible that the optical position *i.e.* the visible light centre does not coincide with the radio position where the jet may play a more important role. In the first instance generally the discrepancies are small, but this work will continue when the accuracy of Gaia position measurement is bound to match that already achieved at radio wavelengths.

Future

At the moment the Gaia focus is fully on the second data release. Gaia DR2 is scheduled for April 2018. This will be a major milestone not only for Gaia, but for astronomy in a wider context. Gaia provides fundamental information on which further research can be based. Yet Gaia DR2 is not the end, but more products and higher accuracy can be expected in Gaia DR3 and DR4 anticipated for 2020 and 2022. The nominal end of mission was planned for summer 2019, but today we know that the satellite has consumables to continue until mid 2024. The first step in the process of funding the operation in this extended period has been achieved. ESA has made the initial extension approval till the end of 2020. We are convinced that the science provided by Gaia will be so compelling, that the future extensions will be granted as well. We are well underway producing a set of fundamental astronomical data for decades to come.

About the Author

Timo Prusti, Gaia Project Scientist, MSc University of Helsinki 1987, PhD University of Groningen 1992, PostDoc Osservatorio Astrofisico di Arcetri 1992. In ESA since 1993 with ISO and Herschel before joining Gaia 2007.