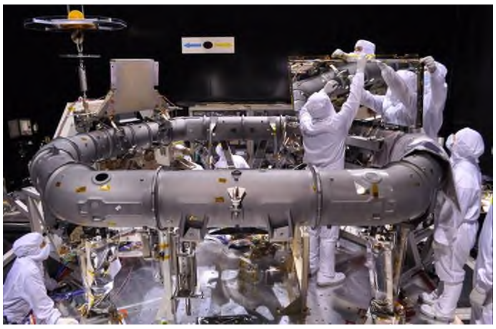
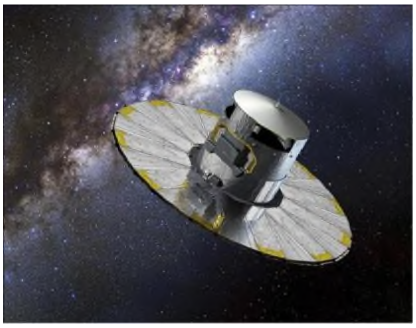
# Gaia sky mapper vs astrometry & astrophysics : News from the orbit

Philippe Tatry, In Orbit Performance and Support for astrometry/astrophysics satellite GAIA, Airbus

Airbus Defence and Space (DS) designed, manufactured, tested/validated and it is ensuring the in-orbit support of the Gaia spacecraft (ESA mission). This spacecraft was launched on 19th of Dec 2013 toward L2 point (i.e. at 1.5 million km from the Earth) and after 5 years of nominal mission, Gaia is in "extended mission".



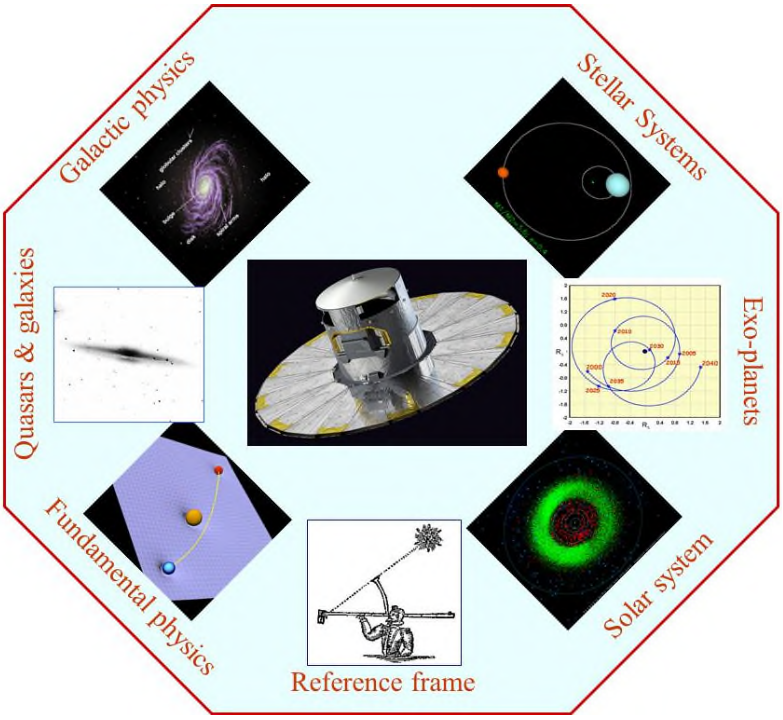


In a nutshell, Gaia mission is dedicated to astrometry & astrophysics with objective to survey more than one billion stars in our Galaxy and beyond in order to provide the largest, most precise 3D map of our Galaxy.

Let’s go further and deeper on Gaia mission … by making a “journey” into its objectives, key-features, general organisation, Science results, technical challenges solved, teams involved and … its next steps. Our guide will be Philippe Tatry who is in charge of the in-orbit support for Gaia at Airbus DS (Toulouse, France).

## What are the Gaia mission objectives ? (key-ones)

Gaia allows astronomers to answer some fundamental questions about the formation & evolution of our Galaxy and to provide insight into many other topical areas of astronomy, such as the history of the Milky Way, the planet detection, the asteroids & Solar System discoveries, the exploding stars (e.g. supernovae) in distant galaxies, the Einstein's General Relativity testing, … as summarized here :



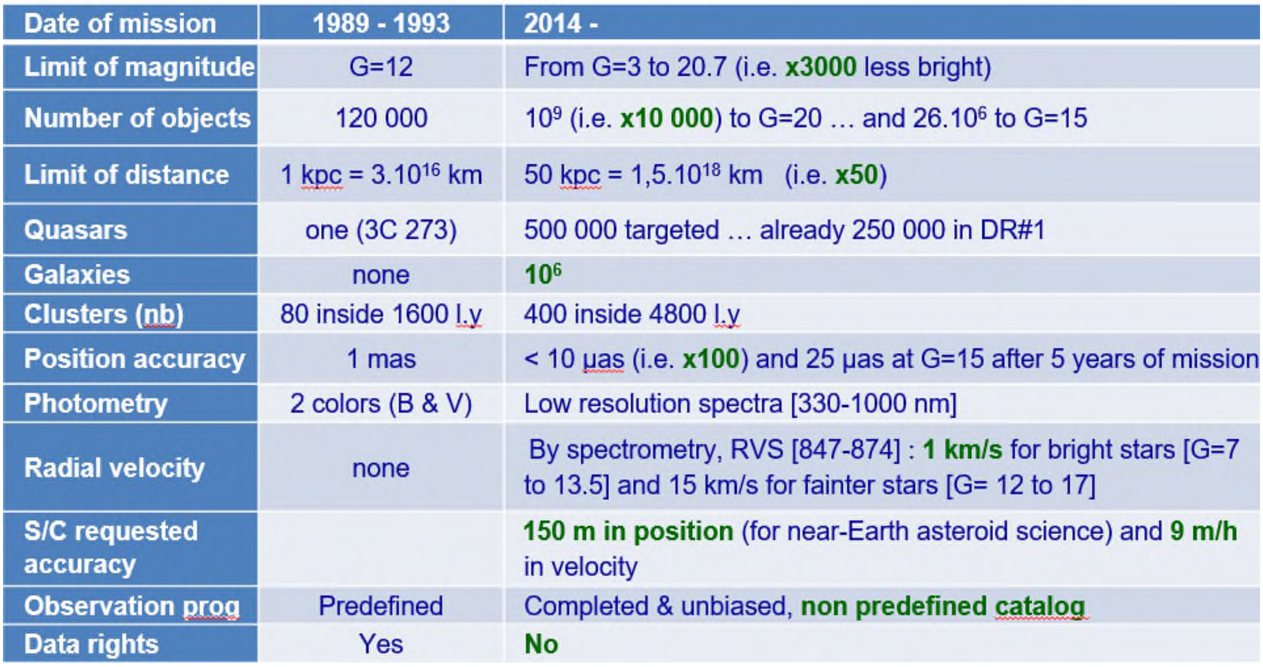
More specifically, Gaia focuses on :

- Astrometry (330<λ<1050 nm) by transforming the location (centroiding) measurements in pixel coordinates to angular-field coordinates through a geometrical calibration of the focal plane. Additionally, further corrections are done on ground to include the systematic chromatic shifts, general-relativistic effects (light bending due to Sun, major planets plus some of their moons and massive asteroids), …

- Photometry (Blue & Red) by estimating the effective temperature (Teff) with an accuracy of 0.3% at G=15 mag and 4% at G=20 mag. It also assesses the metallicity ratio ([Fe/H]), the surface gravity (log(g)) with accuracies of 0.1–0.4 dex, …
- Spectrometry (RVS) by measuring the radial velocities thanks to the isolation of a narrow $\Delta\lambda$ strongly dispersed to see some well-known spectral lines (e.g. Ca lines). For brightest stars, stellar atmospheric parameters are extracted from the RVS spectra (to compare with reference-star spectra libraries using minimum-distance methods, PCA and neural-network approaches), …
- Fundamental Physics in terms of :
  - Light Bending in the Solar System by using the gravitational light bending and measurement of PPN (Parameterized Post-Newtonian) parameter gamma. Gaia will extend the domain of observations by x100 in length-scale and by x$10^6$ in mass i.e. Gaia measurements to provide a precision of $\sim 5.10^{-7}$ for gamma, based on multiple observations of $\sim 10^7$ stars brighter than V=13 mag at wide angles from the Sun, with individual measurement accuracies better than 10 μas.
  - Gravitational Waves (GW) that will not significantly affect the individual position measured by Gaia spacecraft but … the entire Gaia data set will be used to put the strongest limit on $\Omega_{GW}$ (i.e. ratio of energy density in GW to the energy density needed to close the Universe). Gaia will set an upper limit of $\Omega_{GW} < 10^{-6}$ to $10^{-7}$ in the frequency band ($10^{-12}$ - $4.10^{-9}$ Hz) i.e. better than the Big Bang nucleosynthesis limit, and much better than the limit from VLBI or the binary pulsar.

**What are the Gaia key-features?** (main specificities)

1) Gaia is a game-changer vs the previous mission (i.e. Hipparcos) - see the comparison table :



| **Date of mission** | **1989 - 1993** | **2014 -** |
|---|---|---|
| **Limit of magnitude** | G=12 | From G=3 to 20.7 (i.e. **x3000** less bright) |
| **Number of objects** | 120 000 | $10^9$ (i.e. **x10 000**) to G=20 … and $26.10^6$ to G=15 |
| **Limit of distance** | 1 kpc = $3.10^{16}$ km | 50 kpc = $1,5.10^{18}$ km (i.e. **x50**) |
| **Quasars** | one (3C 273) | 500 000 targeted … already 250 000 in DR#1 |
| **Galaxies** | none | **$10^6$** |
| **Clusters (nb)** | 80 inside 1600 l.y | 400 inside 4800 l.y |
| **Position accuracy** | 1 mas | < 10 µas (i.e. **x100**) and 25 µas at G=15 after 5 years of mission |
| **Photometry** | 2 colors (B & V) | Low resolution spectra [330-1000 nm] |
| **Radial velocity** | none | By spectrometry, RVS [847-874] : **1 km/s** for bright stars [G=7 to 13.5] and 15 km/s for fainter stars [G= 12 to 17] |
| **S/C requested accuracy** | | **150 m in position** (for near-Earth asteroid science) and **9 m/h** in velocity |
| **Observation prog** | Predefined | Completed & unbiased, **non predefined catalog** |
| **Data rights** | Yes | **No** |

2) Gaia spacecraft has a very high stability of the observations (up to 10 µas).

3) Gaia mission lasts an in-orbit long duration (> 9 years).

4) Gaia mission provides a very huge volume of data that is 200 Gbits of compressed data per day increasing up to 700 Gbits/day (for high-density areas). Then, around 20 Tera-octets of measurements are collected per year that generated 1 to 3 Peta-octets of data after processing by the ground (during the 5 first years).

5) Gaia involves a wide & complementary community (> 500 people) including ESA, scientists and industry.

6) Gaia offers a wide & free access to all its Science data.

### How is Gaia mission organised ? (overview)

After the “classical” organisation of a development phase (i.e. up to the Gaia in-orbit commissioning), the current organisation is the following :

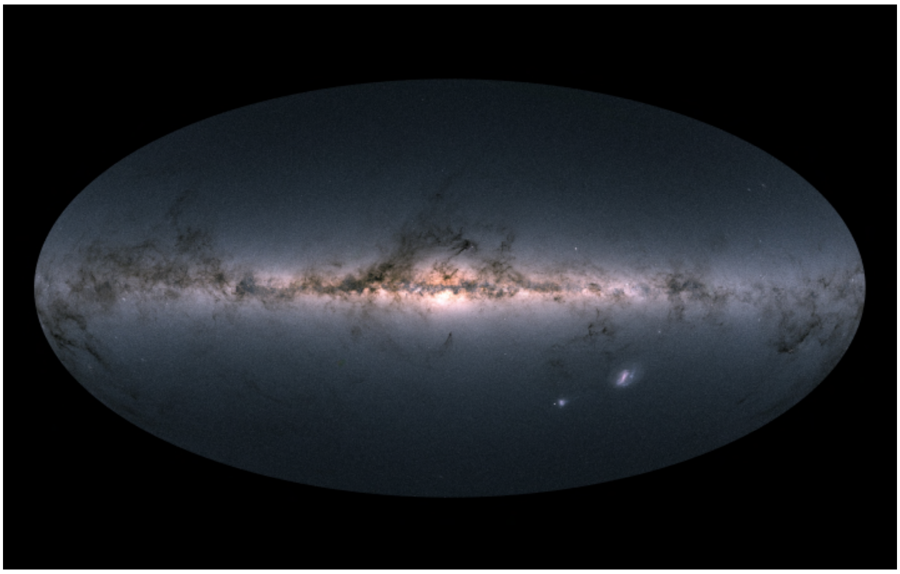
- ESA manages the Gaia mission, coordinates the associated Science (by ESTEC – Research and Technology Centre at Noordwijk, Netherlands), ensures the mission operations (by MOC - Mission Operations Centre at ESA Operations Centre, Darmstadt, Germany) and the science operations (by SOC – Science Operations Centre at ESA Astronomy Centre, near Madrid, Spain).
- DPAC (Data Processing & Analysis Consortium) consists of 450 persons (from 160 institutes located in 25 countries), who contribute to writing the 3 millions of lines of code needed for the data processing and to subsequently operate the software systems and validate the resulting output. The DPAC is subdivided into 9 Coordination Units dedicated to technical aspects, data simulation, astrometric data, binaries & solar system objects analysis, photometric data, spectroscopic data, variable stars analysis, spectral classification and Gaia data publications.
- Airbus Defence and Space : after its prime role of Gaia spacecraft designer, manufacturer & tester, Airbus DS supports the Gaia in-orbit operations (i.e. from the in-orbit commissioning up to now). This support to ESA teams consists of analysing the daily telemetry (> 35,000 parameters) as routine tasks, identifying the trends, detecting some potential off-nominal behaviour and being on-call duty in case of in-orbit anomaly. In that case, Airbus DS participate to the ESA’s ARB (Anomaly Review Boards), perform the analyses/studies (with Airbus DS relevant experts), propose to ESA some work-around solutions in order to recover the situation and it remain an actor up to the full recovery.
- And of course, the Scientists (e.g. astronomers, astrophysicists) as “end-users” of the Gaia data.

### What are the Gaia Science results ? (key-ones, i.e. not exhaustive)

The Gaia Science results are released to the Science wide community via successive Data Releases (DR) vs the number of in-orbit observation months :

- DR1 (14/09/16) - 14 months (25th of July 2014 to 16th of Sept 2015),
- DR2 (25/04/18) - 22 months (25th of July 2014 to 23rd of May 2016),
- Early DR3 (03/12/20) and DR3 (13/06/22) - 34 months (25th of July 2014 to 28th of May 2017).

For illustration, see the Gaia's all-sky view of our Milky Way Galaxy and neighbouring galaxies, based on measurements of around 1.8 billion stars :



The next table provides the number of sources collected by Gaia vs the DR.

| | **DR3** | **DR2** | **DR1** |
|---|---|---|---|
| **Total number of sources** | **1,811,709,771** | **1,692,919,135** | **1,142,679,769** |
| | **Early DR3** | | |
| Number of sources with full astrometry | 1,467,744,818 | 1,331,909,727 | 2,057,050 |
| Number of 5-parameter sources | 585,416,709 | | |

| | | | |
|---|---|---|---|
| Number of 6-parameter sources | 882,328,109 | | |
| Number of 2-parameter sources | 343,964,953 | 361,009,408 | 1,140,622,719 |
| Gaia-CRF sources | 1,614,173 | 556,869 | 2191 |
| Sources with mean G magnitude | 1,806,254,432 | 1,692,919,135 | 1,142,679,769 |
| Sources with mean $G_{BP}$-band photometry | 1,542,033,472 | 1,381,964,755 | - |
| Sources with mean $G_{RP}$-band photometry | 1,554,997,939 | 1,383,551,713 | - |
| | **New in DR3** | **DR2** | **DR1** |
| Sources with radial velocities | 33,812,183 | 7,224,631 | - |
| Sources with mean $G_{RVS}$-band magnitudes | 32,232,187 | - | - |
| Sources with rotational velocities | 3,524,677 | - | - |
| Mean BP/RP spectra | 219,197,643 | - | - |
| Mean RVS spectra | 999,645 | - | - |
| Variable-source analysis | 10,509,536 | 550,737 | 3,194 |
| Variability types (supervised machine learning) | 24 | 6 | 2 |
| Supervised machine-learning classification for variables | 9,976,881 | 390,449 | 3,194 |
| Specific Object Studies – Cepheids | 15,021 | 9,575 | 599 |
| Specific Object Studies – Compact companions | 6,306 | - | - |
| Specific Object Studies – Eclipsing binaries | 2,184,477 | - | - |
| Specific Object Studies – Long-period variables | 1,720,588 | 89,617 | - |
| Specific Object Studies – Microlensing events | 363 | - | - |
| Specific Object Studies – Planetary transits | 214 | - | - |
| Specific Object Studies – RR Lyrae stars | 271,779 | 140,784 | 2,595 |
| Specific Object Studies – Short-timescale variables | 471,679 | 3,018 | - |
| Specific Object Studies – Solar-like rotational modulation variables | 474,026 | 147,535 | - |
| Specific Object Studies – Upper-main-sequence oscillators | 54,476 | - | - |
| Specific Object Studies – Active galactic nuclei | 872,228 | - | - |
| Photometrically-variable sources with radial-velocity time series | 1,898 | - | - |
| Sources with object classifications | 1,590,760,469 | - | - |
| Stars with emission-line classifications | 57,511 | - | - |
| Sources with astrophysical parameters, BP/RP spectra | 470,759,263 | 161,497,595 | - |
| Sources with astrophysical parameters assuming an unresolved binary | 348,711,151 | - | - |
| Sources with spectral types | 217,982,837 | - | - |
| Sources with evolutionary parameters (mass & age) | 128,611,111 | - | - |
| Hot stars with spectroscopic parameters | 2,382,015 | - | - |
| Ultra-cool stars | 94,158 | - | - |
| Cool stars with activity index | 1,349,499 | - | - |
| Sources with H-alpha emission measurements | 235,384,119 | - | - |
| Sources with astrophysical parameters, RVS spectra | 5,591,594 | - | - |
| Sources with chemical abundances from RVS spectra (up to 13 species) | 2,513,593 | - | - |

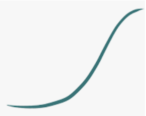
| | | | |
|---|---|---|---|
| Sources with a diffuse interstellar band (DIB) in their RVS spectrum | 472,584 | - | - |
| Non-single stars (astrometric, spectroscopic, eclipsing, orbits, trends) | 813,687 | - | - |
| Non-single stars - orbital astrometric solutions | 169,227 | - | - |
| Non-single stars - orbital spectroscopic solutions (SB1/SB2) | 186,905 | - | - |
| Non-single stars - eclipsing binaries | 87,073 | - | - |
| QSO candidates | 6,649,162 | - | - |
| QSO candidates - redshifts | 6,375,063 | - | - |
| QSO candidates - host galaxy detected | 64,498 | - | - |
| QSO candidates - host galaxy surface brightness profiles | 15,867 | - | - |
| Galaxy candidates | 4,842,342 | - | - |
| Galaxy candidates - redshifts | 1,367,153 | - | - |
| Galaxy candidates - surface brightness profiles | 914,837 | - | - |
| Solar system objects | 158,152 | 14,099 | - |
| Solar system objects - epoch astrometry (CCD transits) | 23,336,467 | - | - |
| Solar system objects - orbits | 154,787 | - | - |
| Solar system objects - average BP/RP reflectance spectra | 60,518 | - | - |
| Solar system objects - planetary satellites | 31 | - | - |
| All-sky total galactic extinction maps at different spatial resolutions | HEALPix levels 6, 7, 8, and 9 | - | - |
| Gaia Andromeda Photometric Survey with light-curves for all objects | 1,257,319 | - | |

**What were the Gaia technical challenges to be solved by the industry engineers ?** (including analogies with "daily-life" features)

As one can imagine, the above objectives, key-features, astrometry & astrophysics results are reachable only because of all the technical challenges were solved by the engineers (industry, …). Even if a complete list of challenges would be out-of-scope of this introduction paper, some of them can be highlighted and illustrated with “daily-life” analogies in order to better understand “what is behind such technical challenges”.

Here, few Airbus DS illustrations **:**

- Very high stability of the observations of sources (accuracy better than 10 µas) that corresponds to the thickness of an hair as seen from … 1000 km ! This stability level is only possible to be reached by mastering all the thermo-elasticity contributors and by controlling all the perturbation elements of the spacecraft attitude.



- Spacecraft attitude is fine-controlled by sets of micro-propulsion thrusters (with thrust ranging in 0-1mN by steps of 1 µN) : with such level of steps, the thrust of … 400 Gaia thrusters would needed to lift a … postage stamp.

- Very high stability of the spacecraft temperature is requested : e.g. on the instrument tore, the temperature stability shall be at … +/- 0,1 mK.

- Gaia observation of objects (e.g. stars, galaxies) up to magnitude 20 : it means with a brightness only 400,000 times (!) lower than the limit of the human eye capability (in the best conditions).

- Gaia on-board atomic clock (Rubidium 87 based) has an accuracy such as its MTIE (Max. Time Interval Error) corresponds to an error of 1 second on … 315 000 years.

- Gaia spacecraft accuracy in position needs to be better than 150 m (for the near-Earth asteroid science) on a distance of 150 million km that corresponds to a relative error less than $10^{-9}$ ! The spacecraft accuracy in velocity has to be lower than 2.5 mm/s corresponding to a relative error less than $10^{-5}$.

**How the several teams are gathered in one "Gaia team" ?** (one project, one team)

The key-words to well characterize the “Gaia team” are collaboration, cooperation, complementarity, reactivity and diversity of people.

Indeed, "People" are the prime-factor to ensure the success of the day-to-day in-orbit lifetime, and this is particularly a key-driver for very complex missions (i.e. on cutting-edge spacecraft and operations) that are not – by consequence – flawless despite any upstream efforts that may lead to a very efficient development phase. In the case of Gaia mission, the mind-set, approach, and practical implementation are based on some underlying principles :

- An end-to-end and multidisciplinary way of working which breaks the walls and promotes the synergies between the spacecraft designers (system, attitude & orbit control, data handling, communications, thermal behaviour, materials), the spacecraft operators (TM/TC exchanges, routine & emergency procedures, 24/7/365 on-call duty), the ground segment specialists (antennas & data flow) and the Science teams (acting as “end users” of the mission). This allows to create complementary viewpoints from within this “integrated team”.
- A continuous enhancement of the know-how throughout the mission duration : daily passes and support during in-orbit operations strengthen the very detailed knowledge of the spacecraft functioning and behaviour (e.g. the 35,000 TM parameters acquired requires time and experience to understand).
- The in-house capability to trade-off criteria as incidents occur in order to target a “users oriented” approach, i.e. oriented to answer to the question “what is best for this particular mission’s end goals ?”.
- The technical and operational creativity (i.e. avoidance of the “Not Invented Here” syndrome) to anticipate and to cope with glitches, unexpected trends, off-nominal situations, failures, … on both hardware and/or software, by generating innovative ideas, new potential solutions, preventive actions and recovery actions.

**What will be next steps ?**

Gaia teams will issue the next DRs :

- Gaia FPR - Focused Product Release (Q4 2023) that will be consisting of ***(i)*** updated astrometry for Solar System objects, ***(ii)*** astrometry & photometry from engineering images taken in selected regions of high source density, ***(iii)*** first results of quasars' environment analysis for gravitational lenses search, ***(iv)*** extended radial velocity epoch data for Long Period Variables, ***(v)*** Diffuse Interstellar Bands from aggregated RVS spectra.
- DR4 (2025) based on 66 months of observation (i.e. from 25th of July 2014 to ~25th of Jan 2020) and that will be consisting of ***(i)*** full astrometric, photometric and radial-velocity catalogues, ***(ii)*** all available variable-star and non-single-star solutions, ***(iii)*** source classifications plus multiple astrophysical parameters, ***(iv)*** exoplanet list, ***(v)*** all epoch and transit data for all sources. Note that DR4 size will be ~ 500 TB (to be compared with DR3 ~ 10 TB i.e. x50) due to inclusion of so-called “epoch data” = basic astrometric CCD measurements & raw BP/RP/RVS spectra for the first time.
- DR5 as DR final that is targeted for end of 2030 – 10.5 years of data from the nominal and completed extended mission, including legacy archive.