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The End Is the Beginning Is the End, Is the Beginning

A Farewell to Gaia: End-of-Life Technology Tests, Spacecraft Disposal and Passivation

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Abstract

ESA's Gaia mission was launched on the 19th of December 2013 and started routine science operations in a Lissajous orbit around the Sun-Earth second Lagrange point (L2) in July 2014. Since then, Gaia has performed more than 15,300 sky scans during its 20+ revolutions around L2, collected upwards of 142 TB of data, measured the properties of 1.8 billion stars, collected information about 150,000+ solar system objects, identified 200+ exoplanet candidates and 4.8 million galaxy candidates, and discovered 3 black holes, among many other notable scientific and technical achievements.

On the 15th of January 2025 routine science operations came come to an end, as the micro-propulsion system that maintains Gaia's precise pointing ran out of gaseous nitrogen (GN2). A small amount of GN2 was left in the tanks and used to perform a series of end-of-life tests that could not have been performed during routine science operations. Some of the main tests aimed at resolving one big mystery surrounding Gaia's payload, namely the unexpected movement and unexplained change in the relative alignment of the two Gaia telescopes, while others tested some of the platform subsystems in preparation for future missions.

After the tests, Gaia performed two disposal manoeuvres that placed the spacecraft into a Heliocentric orbit with a very low probability to return to the Earth-Moon system within the next 100 years. The spacecraft was then passivated on the 27th of March 2025, putting an end to more than 11 years of spacecraft mission operations.

Although this is the end of mission operations the work is far from over for the Gaia team. With two more major data releases to come in the following years (DR4 and DR5), there still a wealth of discoveries waiting to be revealed in Gaia's data.

This paper begins by introducing the Gaia mission, its scientific principles and the spacecraft and ground segment. It then reviews some of the key activities and experience gained when planning and conducting the end-of-life activities, including the on-orbit technology tests and the spacecraft disposal and passivation.

Keywords: mission operations, spacecraft disposal, spacecraft passivation, end-of-life, on-orbit testing

Acronyms/Abbreviations

BAM	Basic Angle Monitor
BAV	Basic Angle Variation
CPS	Chemical Propulsion System
DDOR	Delta-Differential One-way Ranging
DPAC	Gaia Data Processing and Analysis Consortium
DR	Data Release
DSA	Deployable Sunshield Assembly
EEPROM	Electrically Erasable Programmable Read-Only Memory
EPSL	Ecliptic Pole Scanning Law
ESA	European Space Agency
ESOC	European Space Operations Centre
FDIR	Failure Detection, Isolation and Recovery
GMSK	Gaussian Minimum Shift Keying
GN2	Gaseous Nitrogen

LEOP	Launch and Early Orbit Phase
LTDP	Long Term Data Preservation
MOC	Mission Operations Centre
MPE	Micro-Propulsion Electronic
MPS	Micro Propulsion System
MT	Micro Thruster
NSL	Nominal Scanning Law
OBC	Onboard Computer
OSR	Optical Solar Reflector
PAA	Phased Array Antenna
PM	Processor Module
RS	Reed-Solomon coding
SAA	Solar Aspect Angle
SDMP	Space Debris Mitigation Plan
SEL	Sun-Earth Libration point
SKM	Station Keeping Manoeuvre
SOC	Science Operations Centre
SSCE	Sun-SpaceCraft-Earth angle
TTC	Telemetry, Tracking & Commanding
TTR	Telemetry, Telecommand and Reconfiguration module

1. The Gaia Mission

1.1 Astrometry Through the Ages

Humankind has been measuring the position of the stars for millennia. Astrometry, the science of precisely measuring the positions and movements of celestial bodies, is one of the oldest branches of astronomy and forms the foundation for understanding the structure and dynamics of the universe. Hipparchus, the Greek astronomer from the 2nd century BCE, is often credited with compiling the first known comprehensive star catalogue listing about 1,000 stars and their positions.

Initial catalogues were limited in number of sources and their accuracy. Over the centuries astrometry made slow but steady progress as the quality of the instrumentation improved (Fig. 1). Tycho Brahe, the Danish astronomer of the 16th century, built sophisticated instruments to measure positions of stars and planets with unprecedented accuracy for his time. His detailed records, particularly of Mars, provided critical data that later enabled Johannes Kepler to formulate his laws of planetary motion. In the 19th century, Friedrich Bessel made the first successful measurement of a star’s parallax. Over time, photographic techniques and better instruments allowed for the creation of increasingly detailed star catalogues.

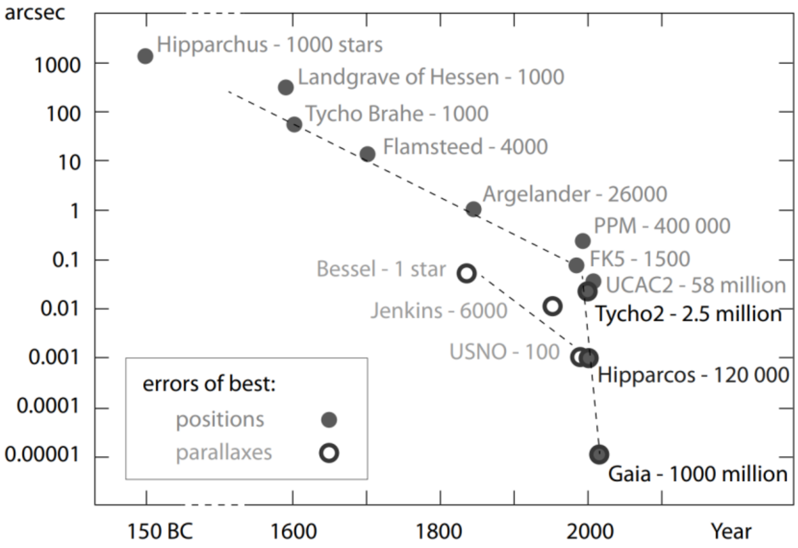


Fig. 1. Astrometric accuracy through the ages [1]

After several centuries of a more-or-less logarithmic improvement in accuracy, space-based measurement techniques came to revolutionise astrometry (Fig. 1).

First with the Hipparcos mission, launched by the European Space Agency (ESA) in 1989 to measure the positions, parallaxes, and proper motions of approximately 118,000 stars with unprecedented precision for the time. Hipparcos established that absolute parallaxes could indeed be determined from space observations, following the suggestion by Pierre Lacroute (1906 – 1993), the French astronomer that in the 1960s first proposed the idea of using a space-based telescope with two widely separated fields of view, superimposed at the same focal plane. The possibility to measure accurate relative star positions over wide separations on the sky unlocks the possibility of constructing a rigid global stellar reference system

Then with ESA's Gaia mission, the last in the long history of astrometry and set to revolutionise the field. Following the same measurement principles as the Hipparcos mission, Gaia raises once again the bar in scientific ambition, designed to measure the positions and other properties of about 1 billion stars with an accuracy down to the microarcseconds range. The reality, however, proved to be more prolific than initially thought.

1.2 Gaia Space and Ground Segments

The Gaia mission was launched on the 19th of December 2013 aboard a Soyuz-Fregat ST rocket from French Guiana, near Kourou, and is operated by the European Space Operations Centre (ESOC) in Darmstadt, Germany. Gaia is a cornerstone mission of ESA, building on the successful legacy of the Hipparcos mission to tackle one of astronomy's most fundamental and challenging tasks: producing an ultra-precise three-dimensional map of approximately one billion stars, reaching magnitudes as faint as 20, within our Galaxy and beyond.

After launch, Gaia was placed into a transfer trajectory towards the second Lagrange point (L2) in the Sun-Earth system (Fig. 2) using a direct and rapid transfer to L2. To accomplish this, the Fregat upper stage first placed Gaia into an intermediate parking orbit. Subsequently, a second engine burn placed Gaia onto its transfer orbit, which was designed to reach L2 within approximately one month. Upon arrival at L2, the spacecraft executed a two-step insertion manoeuvre to enter a Lissajous orbit around the Libration point. Like other space observatory missions such as Herschel and Planck, Gaia operates from this orbit at L2, selected primarily for its stable thermal conditions and minimal interference from Earth and Moon in observing the sky.

Gaia's primary objective is to carry out global astrometry. To achieve this, the spacecraft is equipped with two telescopes aligned along distinct astrometric viewing directions—referred to as line of sight 1 and 2, as illustrated in Fig. 2—separated by a fixed angle of 106.5°, known as the Basic Angle. Both telescopes share a common focal plane where the detectors are located. This configuration enables precise measurements of stellar positions by comparing observations from both lines of sight, which lie in a plane perpendicular to Gaia's spin axis.

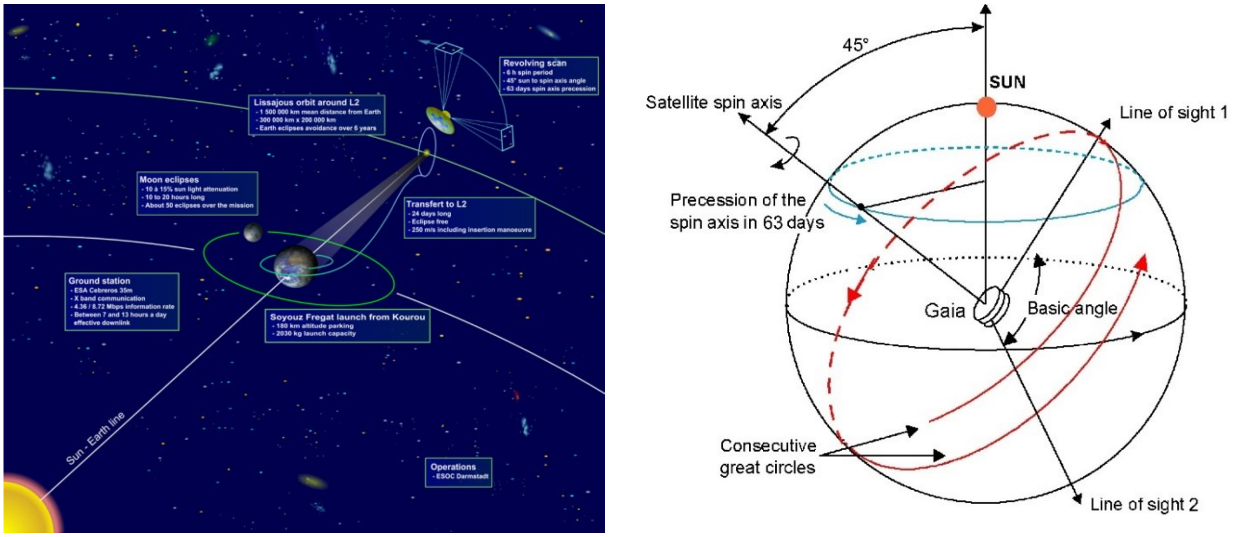


Fig. 2. Gaia trajectory (left), and nominal scanning law (right) [2]

Gaia operates in a continuous scanning mode, rotating around its spin axis to allow the two fields of view to sweep across the sky at a nominal rate of 1° per minute, completing a full rotation approximately every six hours. The spacecraft maintains a Sun Aspect Angle (SAA) of 45°, defined as the angle between the spin axis and the direction toward the Sun. This angle was chosen as a trade-off to balance measurement performance with design limitations, including thermal control, power generation, and shielding of the payload from direct solar radiation. Additionally, the spin axis undergoes a slow precession, completing a full cycle roughly every 63 days (Fig. 2). This precession enables Gaia to achieve full sky coverage within a few months. Over time, the dual lines of sight trace out a series of great circles on the celestial sphere, ensuring that each star is observed multiple times along different scan directions throughout the mission's duration. Except for a special period known as the Ecliptic Pole Scanning Law (EPSL), which was employed during commissioning and the early routine phase, Gaia follows a consistent and stable scanning strategy known as the Nominal Scanning Law (NSL) for the majority of the mission.

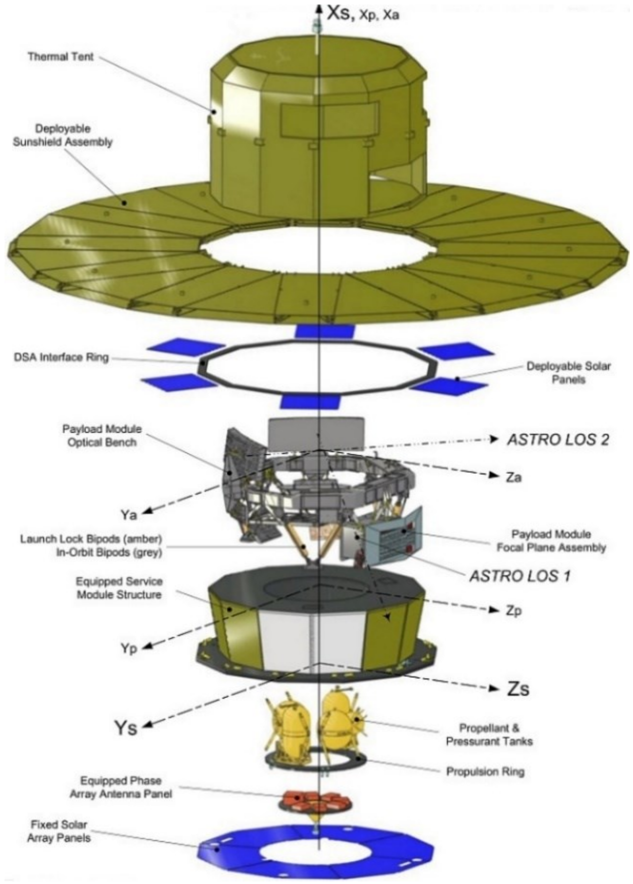


Fig. 3. Gaia spacecraft exploded view (ESA)

Fig. 4. Gaia in the fairing (left), and with the Deployable Sunshield Assembly (DSA) fully deployed at Astrium Toulouse (right)

The Gaia spacecraft incorporates a significant number of custom-built components, required by its extreme precision goals. Its digital camera, the largest ever deployed in space, comprises 106 CCD sensors, with a light efficiency of around 90% (compared to roughly 20% for standard terrestrial cameras). The telescope is coupled to the onboard attitude control system, enabling highly accurate rate measurements and achieving a total control error equal to one full rotation every 410 years. For Gaia thermal and pointing stability are key. Movable components are kept to a minimum (e.g., no reaction wheels or mechanically driven antennas). Data transmission is handled via a new (at design and construction time) type of electromagnetically steerable Phased Array Antenna (PAA), while fine attitude control is managed by a cold gas Micro Propulsion System (MPS), flown for the first time on Gaia, and that provides thrust in the range of few µN to 1 mN. Timestamping relies on a highly accurate atomic clock.

The Gaia ground segment consists of several key components distributed across Europe. The Mission Operations Centre (MOC), located at ESOC in Darmstadt Germany, which is responsible for mission operations planning, execution, and monitoring, as well as for controlling both the spacecraft and the operations ground segment. The MOC also oversees the network of Ground Stations, which are part of ESA's tracking infrastructure. This network includes Deep Space antennas used during the commissioning and routine phases of the mission, along with a set of 15-meter antennas deployed during the Launch and Early Orbit Phase (LEOP) and other critical operations. These stations maintain continuous communication with the spacecraft in X-band for both uplink and downlink, and are also employed for ranging, Doppler, and Delta Differential One-way Ranging (DDOR) measurements used in orbit determination.

Scientific operations are managed by the Science Operations Centre (SOC), located at ESAC in Villafranca Spain. The SOC handles scientific planning, monitors the performance of the payload using telemetry provided by the MOC, and coordinates closely with the Gaia Data Processing and Analysis Consortium (DPAC). It is also responsible for data archiving, distribution, and providing support for scientific analysis.

The DPAC, in turn, is a large international collaboration of scientists and engineers responsible for processing, analysing, and validating all the scientific data collected by Gaia. Their ultimate goal is to produce the Gaia star catalogue, the mission's primary scientific output. The DPAC operates under ESA's coordination, but the consortium itself is largely made up of European research institutes and observatories, making it one of the largest scientific collaborations in astronomy today.

Supporting the overall mission operations are the industrial contractors, who not only delivered the spacecraft to ESA but also provided key assets such as the spacecraft database, flight dynamics database, and onboard software. The team of industrial contractors continue to offer post-launch technical support to the MOC, ensuring sustained operational reliability.

1.3 All Good Things Come to an End

The Gaia spacecraft relied on its MPS, with its set of six redundant Micro Thrusters (MT), to maintain its highly accurate pointing, paramount for the required very high astrometric accuracy. Overall, the MPS performed well throughout the mission, meeting and surpassing the rate stability requirements in the 0.1 mas/s range [3]. The micro thrusters are fed by gaseous nitrogen (GN2) and controlled by a Micro-Propulsion Electronic unit (MPE).

From the start, Gaia's astrometric mission was bound to end at the latest once the nitrogen gas was exhausted. The GN2 consumption was closely monitored on board, and the team developed a model on ground to predict the future evolution (pressure) of the remaining gas. At the normal rate of consumption, it was predicted that the GN2 would run out (i.e. pressure below the minimum required for nominal/qualified MPS operations) at the beginning of February 2025, thus setting the date for the end of the mission.

However, before the Nitrogen gas was to be completely exhausted the team had one last job for Gaia. Gaia was to serve as a testbed to help:

- Improve the knowledge about the Gaia mission.
- The implementation of future missions.

The team agreed to end science acquisition on the 15th of January 2025 at 06:15 UTC and use the remaining approximately 2 weeks equivalent of astrometric cold gas for the end-of-life technology tests, ending almost 10.5 years of routine operations. From the 24th of July 2014 to the 15th of January 2025 Gaia:

- Made 3 trillion observations.
- Observed 2 billion different celestial objects, including stars, galaxies, and asteroids.
- Consumed 55 kg of nitrogen gas to keep its stable pointing.
- Performed more than 60 station-keeping manoeuvres.

- Used 50,000 hours of ground station time to downlink science and housekeeping data.
- Received and executed 2.8 million commands from ground.
- Downlinked more than 142 terabytes of data.
- Gave rise to more than 13,000 refereed scientific publications.
- Among many notable scientific and technical achievements.

2. Gaia as a Platform for End-of-Life Testing

At the end of a successful operational phase, it is standard practice to carry out end-of-life tests prior to spacecraft disposal. These tests are designed to assess component performance in ways typically avoided during normal operations, since they involve risks of damage or reduced efficiency. Conducting such tests provides valuable insights into subsystem performance limits, benefiting the development and operation of future missions. Consequently, testing may involve activating unused modes or operating units in intentionally degraded configurations.

Future science missions, including the gravitational wave observatory LISA and the proposed next-generation astrometry mission GaiaNIR, are anticipated to be even more sensitive and may significantly benefit from Gaia's operational experience. For Gaia specifically, a key objective for additional end-of-life testing was to investigate the cause of the spacecraft's Basic Angle Variations (BAV). Despite extensive analyses conducted early in the mission, this issue remains inadequately understood.

The Gaia team started collecting and discussing ideas for tests in 2023 involving all stakeholders. Gaia started out with the initial assumption that "there are no bad test ideas" and this proved a useful approach to collect as broad a spectrum of proposals as possible. After multiple iterations, the team converged on a set of tests grouped in two main categories:

1. Tests to try to improve the understanding of the Basic Angle Variation.
2. Technology tests.

2.1 Understanding the Basic Angle Variation

As depicted in Fig. 2, the Basic Angle is the angle between the instrument two viewing directions on the sky. For Gaia this angle is approximately 106.5°. The Basic Angle Variation, or BAV, refers to the unexpected movement and unexplained shifts in the relative alignment between the two telescopes, which was measured in flight to be several hundred times more than their design-specified limit. This variation was continuously measured on board using the Basic Angle Monitor (BAM). The BAV measurements provided by the BAM equipment are then used on ground in post-processing to help the team properly model the BAV. The BAV has been an issue for Gaia since it was identified immediately after payload switch on. Despite extensive testing and analysis, it has not been possible to identify the root cause of the BAV and remains one of the main open technical mysteries from the commissioning phase.

In absolute terms, the BAV represents a very small displacement; however, it is substantial when considering Gaia's demanding performance requirements. The issue was not detected during pre-launch testing because the BAV was smaller than Earth's ambient noise levels, making orbital testing necessary.

Despite the extensive data collected, the anomaly has never fully aligned with pre-launch thermo-mechanical design predictions. Resolving this discrepancy between predicted and actual behaviour motivates the need for further testing. The concept of most BAV tests is to perturb the system in a way that is different to the normal spacecraft operations. As such, conducting these tests during routine mission operations is undesirable, as they significantly disrupt scientific data collection for extended periods.

The team conducted multiple tests to collect data to better understand the BAV. The most promising one, and also the one that was the biggest driver for the scheduling of the whole end-of-life technology tests phase was the so-called *Sun Aspect Angle Variation*. This test placed Gaia in different thermal conditions by using a series of attitude slews (Fig. 5) to change the Solar Aspect Angle and then measured the BAV. In the end the test had to be split into two parts. The first part ran from the 20th of January to the 26th of February and the second, a much shorter test, ran from 2nd to the 4th of March. Exact timings are given in Table 1 below.

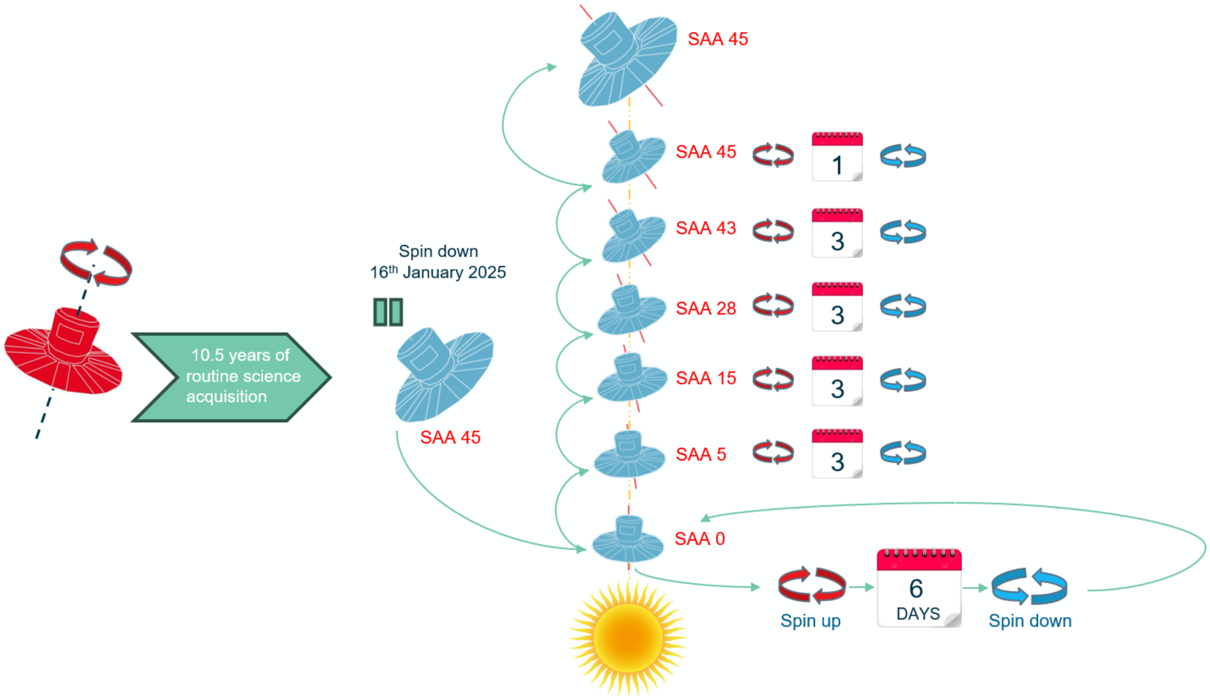


Fig. 5. First part of the Gaia Sun aspect variation test during the end-of-life testing phase (image credits to Ander Martinez De Albeniz from the ESOC Flight Dynamics team)

Table 1. Gaia Solar Aspect Angle during the end-of-life tests

Start (UTC)	End (UTC)	SAA (degrees)
2025-01-20 12:36	2025-01-22 11:23	Slew from 45 to 0
2025-01-22 11:23	2025-02-10 08:45	0
2025-02-10 09:16	2025-02-16 09:12	0
2025-02-16 15:07	2025-02-19 15:05	5
2025-02-19 21:10	2025-02-22 21:08	15
2025-02-23 03:13	2025-02-26 03:11	28
2025-02-26 09:16	2025-03-01 09:14	43
2025-03-01 15:19	2025-03-02 15:15	45
2025-03-02 16:30	2025-03-04 15:27	Slew from 45 to 0
2025-03-04 16:30	2025-03-04 16:38	Slew from 0 to 45

As Gaia slews from its routine Solar Aspect Angle (SAA) at 45° to 0° its brightness increases, making Gaia visible to smaller telescopes from ground. The increase in spacecraft brightness created a chance for outreach and to involve the wider amateur astronomy community in these last months of Gaia mission operations. A call was put out for amateur astronomers to observe Gaia during this period. Observations were received from around the world and compiled on the ESA Gaia webpage here [4].

2.2 Preparing the Future

The second group of tests was more technology focused, and were run to assess the impact of aging on some systems and to operate some units in different conditions in preparation for future missions

including:

- **Phased Array Antenna (PAA) in toroidal beam mode**: in routine operations the Gaia TM transmission chain uses Gaussian Minimum Shift Keying (GMSK) modulation with a symbol rate of 10 Msps. The signal is then fed to the Phased Array Antenna (PAA), which uses electronic beam steering to maintain precise pointing of the downlink beam towards the Earth. This configuration is optimized specifically for the mission's design SAA of 45° across all operational modes. This test was designed to better understand the viability of operating the PAA in a different mode known as the "torus mode". In this new mode of operations, the PAA phases are fixed so the antenna radiates uniformly in all azimuthal directions.

- **Micro Propulsion System (MPS) unit tests**: these tests were run to assess the impact of aging on the MPS performance in a wide range of operating conditions. This characterization will contribute to the in-depth study phase of the upcoming ESA LISA mission, which will use a similar system, and the advancement of cold gas systems for upcoming missions. These tests involved operating the micro thrusters at different thrust levels and using different thrust profiles.
- **TTR without Reed-Solomon coding**: the Telemetry, Telecommand and Reconfiguration (TTR) module, part of Gaia's onboard computer, provides the digital data to the transponder. In routine operations Gaia uses GMSK modulation with no convolution coding. Still, there is a Reed-Solomon (RS) EDAC applied to the bitstream by the TTR. This test disabled the Reed-Solomon coding and measured the frame error rate on ground.

2.3 No Plan Survives First Contact with Reality

The Sun Aspect Variation test was the main driver for this phase. Thermal stability was key, and it was important that the spacecraft was thermally stable before starting the test. It was decided that the Sun Aspect Variation test would be one of the first tests to run, as the spacecraft exists its already stable science acquisition mode. During the initial planning enough margin was placed between the start of the end-of-life testing phase and the first disposal manoeuvre, scheduled for the 7th of March, to accommodate any delays in the execution of the tests.

As anyone working in operations knows: "no plan survives first contact with reality". During the initial slew to SAA 0° the spacecraft entered a Safe Mode, which in Gaia means the switch off of many of the subsystems leading to a large thermal disturbance. The Sun Aspect Variation test had to be interrupted until the thermal stability could be restored, introducing a delay of approximately 3 weeks in the test schedule. The built-in margin in the schedule was enough to accommodate the delay and even to introduce a new Sun Aspect Variation test just in time for the first disposal manoeuvre on the 7th of March.

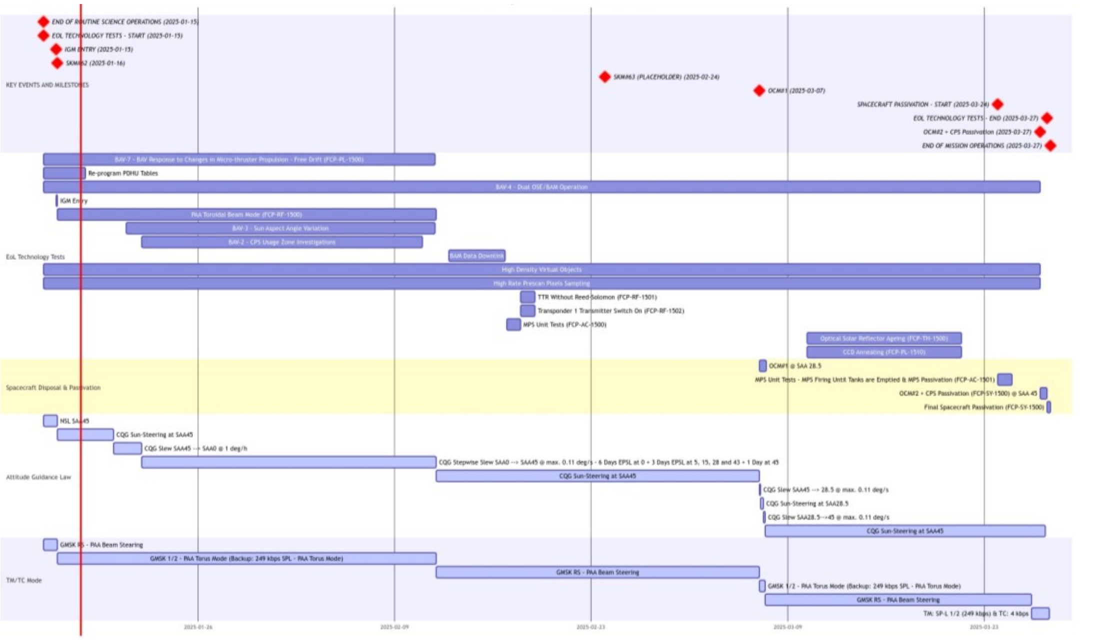


Fig. 6. Timeline at the start of the end-of-mission operations phase (the plan)

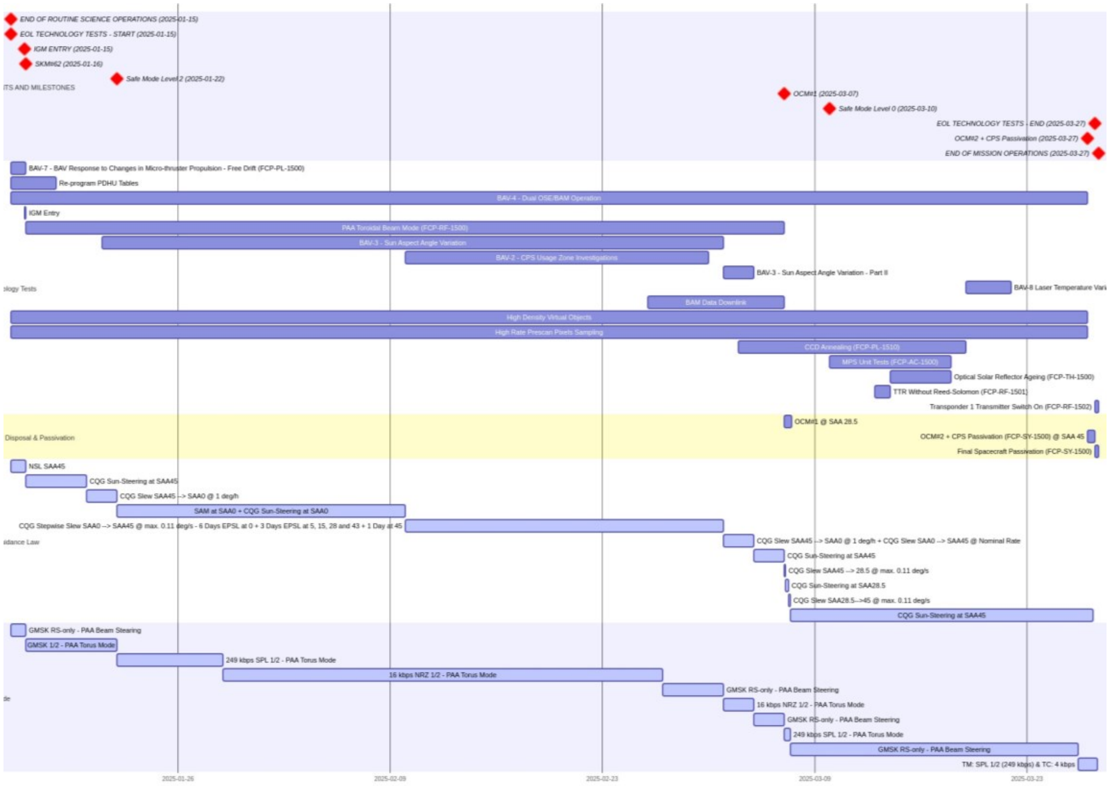


Fig. 7. Timeline at the end of the end-of-mission operations phase (the reality)

Tests initially planned for execution before the first manoeuvre were rescheduled for after the manoeuvre with no significant impact on their performance or results. A second Safe Mode on the 10th of March, that was quickly recovered by the team, introduced a few more delays in the testing but again, and due to the margins in the schedule, with no impact on the outcome of this test phase.

In the end, and despite the two safe modes and the need to continuously adapt the on-orbit technology testing schedule, the team did manage to complete all scheduled tests and even added a few more that were not initially planned thanks to rapid feedback of results during the phase itself.

3. Spacecraft Disposal and Passivation

3.1 Space Debris Mitigation and ESA’s Clean Space

The orbits of space systems around the Sun-Earth Libration (SEL) points 1, 2 and 3 (collinear Libration points) are unstable since natural perturbations can lead the space system to return to Earth orbits, or re-enter. For these orbits, the ESA Space Debris Mitigation Policy and Requirements [5][6] fully apply such as to avoid that debris are generated or can return to Earth orbits [7]. Successful disposal from SEL orbits implies disposal into Heliocentric orbits with no revisit closer than 1,5 million km to Earth or negligible probability to interfere with the Earth sphere of influence considering the space system area-to-mass ratio distribution within the next 100 years [7].

Even though the Gaia mission has no Space Debris Mitigation Plan (SDMP) and is not formally obliged to comply with the requirements since the mission was launched before the policy came into force, it was agreed to still follow the best practices and try to adhere to the requirements as much as possible. In line with the requirements defined for upcoming ESA missions to SEL 2 Ariel and Plato, it was agreed that:

- The disposal manoeuvres shall ensure that the likelihood of Gaia returning to the Earth-Moon system in the next 100 years is < 10%, however,
- Given the amount of propellant still available in the tanks the goal was to reduce the probability further and stay close to 1%.

It was further agreed that the disposal manoeuvres will be used to deplete as much propellant as possible, as long as it does not negatively affect the Earth-Moon return probability. Priority is given to achieving the target (low) return probability, at the expense of leaving a bit more propellant in the tanks. Even though venting the tanks was not option in Gaia by design, analysis showed that the residual propellant left in the tanks was not a concern.

3.2 Gaia Disposal Strategy

Gaia's Chemical Propulsion System (CPS), used for all orbital control manoeuvres including the SEL 2 insertion manoeuvres, all 60+ Station Keeping Manoeuvres (SKM) and now the disposal manoeuvres, had been operating in blow-down mode since 2015. Propellant bookkeeping estimated that the CPS could deliver approximately 50 m/s if it were to operate at inlet pressures within the thrusters' acceptance box and could deliver up to 75 m/s if it were to operate the thrusters at the low end of the qualification box, with the oxidant (Nitrogen Tetroxide) pressure down to ~12 bar and the fuel (Monomethyl Hydrazine) pressure down to ~10.8 bar. But could we go lower and deplete more propellant?

Rosetta, an ESA mission in the meantime retired, had embarked very similar thrusters to Gaia. An onboard failure early in the mission made it such that the CPS had to be operated in blow-down for most of the mission. Ground tests conducted in 2008 and later the actual flight data, showed that the Rosetta CPS thrusters could operate well below their qualified inlet pressures (down to ~8.2 bar for the oxidant and ~7.5 bar for the fuel) while still maintaining thrust stability.

The data from Rosetta gave the Gaia team confidence that we could venture outside the qualification box of the thrusters to deplete more propellant. In the end, it was agreed:

- To baseline the remaining $\Delta \mathbf{V}$ as 75 m/s, bringing the thrusters to edge of the qualification box.
- To limit the maximum remaining $\Delta \mathbf{V}$ taking 100% margin with respect to the baseline, i.e., 150 m/s.
- That given the uncertainty around the performance of the thrusters outside the qualification box the disposal analysis should be robust to total disposal $\Delta \mathbf{V}$ in the range [60, 160] m/s, where 60 m/s is close to the thrusters' acceptance box.

The total ΔV available for the disposal is only one of several constraints that had to be taken into account when devising the disposal strategy. Some of the key drivers and constraints for the disposal strategy were:

- **Return probability to the Earth-Moon system**: the probability of Gaia returning to the Earth-Moon system within the next 100 years shall be below 10%, with the goal to stay close to 1%.
- **CPS passivation**: reduce as much as possible the amount of fuel and oxidant left in the tanks, as long as it does not negatively impact the Earth-Moon return probability.
- **Total $\Delta \mathbf{V}$ for disposal**: the disposal strategy shall be robust to a total available $\Delta \mathbf{V}$ for disposal between 60 and 160 m/s.
- **Operations complexity**: simplify operations, resort mostly to flight-proven operations and procedures and stay within known conditions/boundaries, including:
    - Minimise the number of disposal manoeuvres.
    - Use only CPS thrusters 1 to 4 (Gaia has 8 redundant CPS thrusters in total in various alignments) to simplify the manoeuvre execution.
    - Execute the manoeuvres and passivation in the vicinity of SEL 2 such as to maintain the routine nominal Earth-S/C distance and Sun-Spacecraft Earth (SSCE) angle.
    - Stay as close as possible to the nominal attitude at SAA 45°.
- **Drift duration**: in case of two or more disposal manoeuvres, shorten the drift duration as much as possible, ideally to one to two months. This requirement is mostly driven by:
    - The desire to reduce the costs associated to the day-to-day operations and to maintaining the flight control team
    - Technical constraints, since a longer drift duration leads to an increasing Earth-Spacecraft distance and SSCE for final passivation activities and an associated degradation of the TM link budget.
- **Station coverage**: final disposal manoeuvre and passivation operations to be conducted using an ESA station. Although Gaia has used third-party stations throughout the mission, the preference for such a critical phase is to use our own stations since it gives us more flexibility and control if we were to face problems during the activities.
- **Timing**: final disposal manoeuvre and passivation to happen approximately 2 months after the end of the science acquisition phase and to be performed during working hours.

An exhaustive search was ran looking for feasible opportunities with manoeuvres falling between the 15th of January and the end of July 2025 and that bring the Earth-Moon return probability close to 1% while fulfilling all other constraints. In the end, the disposal strategy consisted of two manoeuvres:

- A small first manoeuvre to depart the routine SEL2 Lissajous orbit along the unstable manifold direction at SAA ~28.5° on the 7th of March starting at ~18:30 UTC and with a size of $\Delta \mathbf{V_1}$ = 10 m/s.
- A second manoeuvre to meet the target low return probability and to deplete as much propellant as possible at SAA ~45° on the 27th of March starting at ~06:30 UTC with a size of $\Delta \mathbf{V_2}$ in the range [65, 120] m/s, resulting in a total disposal $\Delta \mathbf{V}$ ($\Delta \mathbf{V_1} + \Delta \mathbf{V_2}$) in the range [75, 130] m/s.

The second disposal manoeuvre was programmed on board to deliver 120 m/s with the knowledge that we could stop the manoeuvre any time after reaching 75 m/s total $\Delta \mathbf{V}$, at edge of the thrusters' qualification box, and still meet the target 1% return probability, as depicted in Fig. 8. All $\Delta \mathbf{V}$ delivered after this point is a "bonus" and is there to deplete as much propellant as possible.

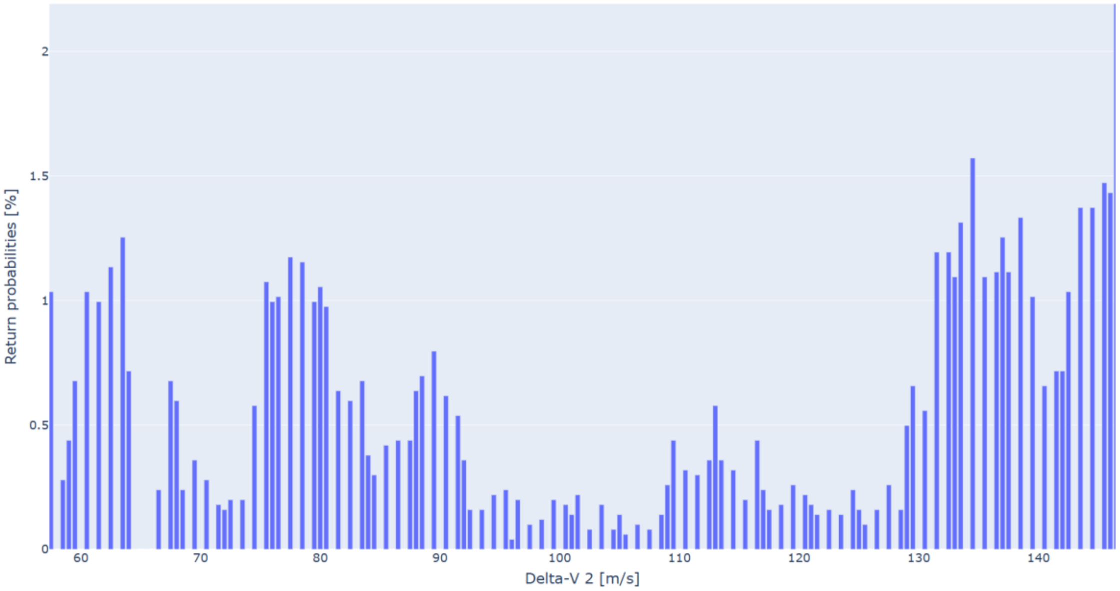


Fig. 8. Sensitivity of the return probability to the size of the second disposal manoeuvre ($\Delta \mathbf{V_2}$)

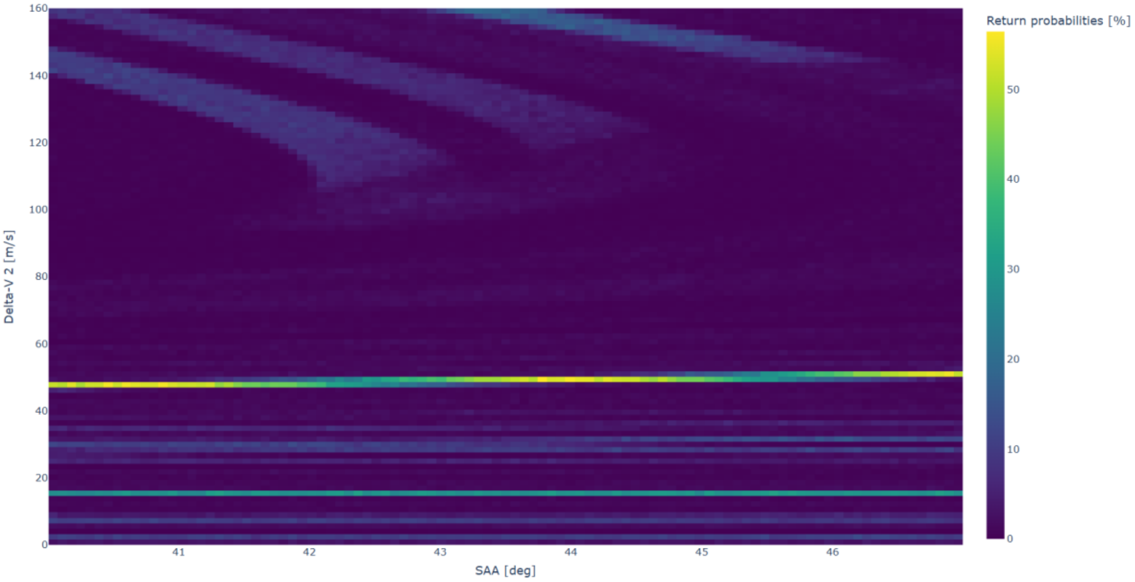


Fig. 9. Sensitivity of the return probability to the size of the second disposal manoeuvre ($\Delta \mathbf{V_2}$) and the thrust direction here measured by the Solar Aspect Angle (SAA)

Fig. 8 depicts the sensitivity of the return probability for a given epoch to changes in the size of $\Delta\mathbf{V_2}$, showing that the strategy is robust to variations in the delivered total $\Delta\mathbf{V}$. Also, and since Gaia also uses the CPS for coarse attitude control during the manoeuvres, the effects of an eventual mis-performance of the thrusters in an increase pointing/attitude error once operating at low inlet pressures was also a concern. Fig. 9 depicts the sensitivity of the return probability to the size of the second disposal manoeuvre (ΔV_2) and the thrust direction here measured by the Solar Aspect Angle, showing that the disposal strategy is robust to changes in the thrust direction of a couple of degrees without impacting the return probability.

To note that the two safe modes experienced during the end-of-mission operations phase did have a small impact on the final sizes of the two manoeuvres without, however, affecting the overall strategy.

The next section describes in more detail the last disposal manoeuvre and passivation steps.

3.3 Second Disposal Manoeuvre and Passivation

The final disposal manoeuvre and passivation were planned such that the whole set of activities would start and finish within the tracking over ESA’s Malargüe station on the 27th of March between 05:00 UTC and 09:50 UTC. To account for possible delays in the manoeuvre or passivation NASA’s Goldstone (antenna DSS-25) and ESA’s New Norcia stations were booked offering almost 12 more hours of continuous visibility. The spacecraft was to be passivated immediately after the end of the disposal manoeuvre.

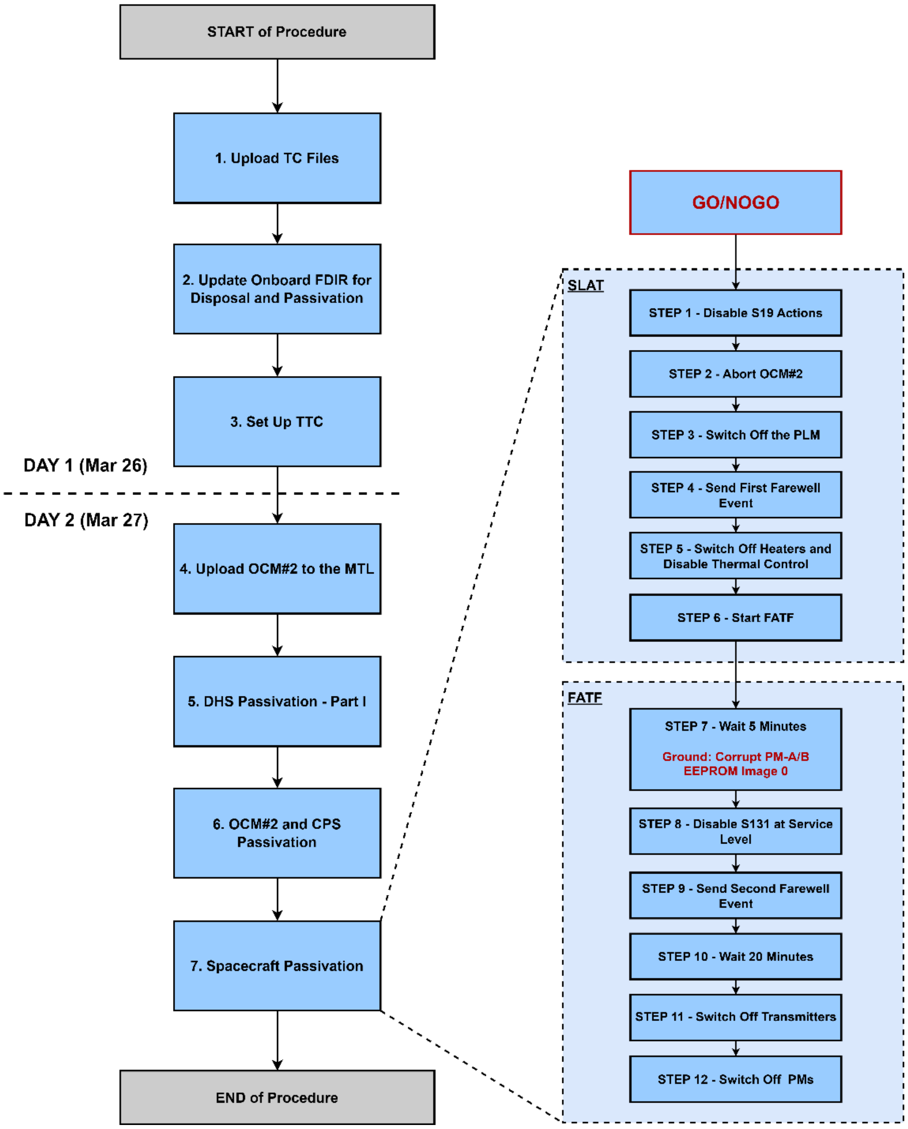
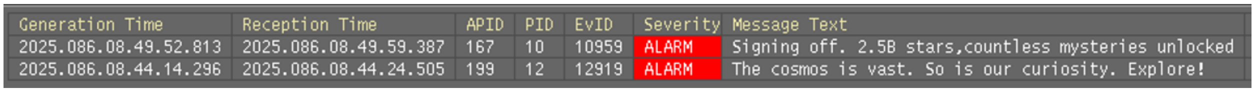


Fig. 10. Final disposal manoeuvre and spacecraft passivation logic

The set of disposal and passivation activities, depicted in Fig. 10, were split in two days, with the 26th being used for some preparatory work (steps 1, 2 and 3) before the actual disposal manoeuvre and passivation the following day on the 27th of March:

- **STEP 1 – Upload TC files**, the team uploaded files to the onboard computer containing pre-defined telecommand sequences to be executed on board at later steps in the passivation sequence. Among the files are the SLAT (So Long and Thanks) and the FATF (For All The Fish) responsible for autonomously executing on board the final spacecraft passivation steps.
- **STEP 2 – Update Onboard FDIR for Disposal and Passivation**, modified the onboard Failure Detection Isolation and Recovery (FDIR) logic from its routine settings in preparation for the activities the next day.
- **STEP 3 – Set Up TTC**, configured the onboard Telemetry, Tracking and Commanding (TTC) system to enable a modulation scheme that allows for simultaneous TM/TC and ranging, and to increase the downlink link margin.
- **STEP 4 – Upload OCM#2 to the MTL**, once the team arrived on console at 05:00 UTC, the first task was to upload the manoeuvre to the onboard timeline for execution at 06:21 UTC to deliver a $\mathbf{\Delta V_2}$ of 120 m/s. At the same time, the onboard timeline was programmed to run one of the TC files to reconfigure the onboard software to disable most of the routine FDIR and leave only a limited set of FDIR settings enabled, once the spacecraft was predicted to have delivered the minimum required to meet the target 1% return probability.
- **STEP 5 – DHS Passivation – Part I**, before the manoeuvre started, the team executed the very first step of the passivation sequence by corrupting two of the Onboard Computer (OBC) software images. To honour the people that contributed to the Gaia mission, one of the images was overwritten with their names and short farewell messages. Gaia is now travelling the Solar system carrying the names of ~1500 contributors and ~140 farewell messages in one of its EEPROMs.
- **STEP 6 – OCM#2 and CPS Passivation**, once the manoeuvre started the task of the ground team was to closely monitor its performance and be ready to abort if needed due to, for example, very high thrust roughness driven by the low inlet pressures reached as the propellant depletes. The manoeuvre completed successfully at 08:34 UTC with a first analysis confirming the actual delivered $\mathbf{\Delta V_2}$ to be very close to the target of 120 m/s (post-analysis confirmed a less than 1% under-performance, remarkable considering the nature of the activity). The CPS, and thrusters in particular, behaved completely nominally throughout the whole manoeuvre, confirming the importance of preserving and using flight data from previous missions when planning this sort of activities, and not rely only on the system specifications and acceptance/qualification margins. The final return probability has been calculated as 0.695% which is an excellent result and a justification for the hard work put into planning the activity by all the teams.
- **STEP 7 – Spacecraft Passivation**, once the manoeuvre completed, ground started the pre-loaded passivation telecommand sequences to passivate Gaia in a controlled way before finally switching off the transmitters followed by the Processor Modules (PM) at 08:54 UTC. As part of the switch off sequence, Gaia took the chance to send two last farewell messages to the team on the ground.



Generation Time	Reception Time	APID	PID	EvID	Severity	Message Text
2025.086.08.49.52.813	2025.086.08.49.59.387	167	10	10959	ALARM	Signing off. 2.5B stars,countless mysteries unlocked
2025.086.08.44.14.296	2025.086.08.44.24.505	199	12	12919	ALARM	The cosmos is vast. So is our curiosity. Explore!

Fig. 11. Farewell messages sent by Gaia

In parallel with the technical work, ESA organized an event bringing together the Gaia community not only to say goodbye to their beloved spacecraft but also to raise awareness for what is still to come for the Gaia mission. As a nod to this future, two ESA trainees, selected through an ESA-internal competition, got the chance to send the last commands to Gaia.

4. The Work is far from Over

Although spacecraft mission operations have come to an end, and Gaia no longer collects data, the Gaia mission is far from over. The Gaia consortium has so far published three Data Releases (DR) covering ever increasing periods of data acquisition:

- DR#1 published in 2016 with observations spanning the period 25 July 2014 - 16 September 2015.
- DR#2 published in 2018 with observations spanning the period 25 July 2014 - 23 May 2016.

- DR#3 published in 2022 with observations spanning the period 25 July 2014 - 28 May 2017.

Still to come are DR#4, expected in 2026 and DR#5 with the complete Gaia legacy archive with all data, expected in 2030.

5. Conclusions

Gaia's end of mission operations phase ran for slightly longer than 2 months, starting on the 15th of January, and finishing on the 27th of March 2025 with the final disposal manoeuvre and spacecraft passivation.

This phase turned out to be more intensive and challenging than the team had perhaps initially expected. After 10.5 years of nearly routine operations, placing Gaia in new flight regimes did prove a challenge with echoes of the commissioning phase in early 2014, with some team members calling it a "reverse commissioning". In the end, and despite the two safe modes and the need to continuously adapt the on-orbit technology testing schedule, the team did manage to complete all scheduled tests and even added a few more that were not initially planned thanks to rapid feedback of results during the phase itself.

Looking back at these last two months of mission operations, we want to highlight some key takeaways that may be of use for future missions entering this phase:

- If you have the chance to run on-orbit tests after the end of the nominal mission phase, do it and involve as many stakeholders as possible. Start the process well in advance and take time to collect and discuss proposals for tests. Gaia started out with the initial assumption that "there are no bad test ideas" and this proved a useful approach to collect as broad a spectrum of proposals as possible.
- Start with the definition and analysis of the disposal strategy early enough. As we ran through the analysis and the details of the disposal manoeuvres and passivation started to take shape, more and more constraints surfaced, requiring multiple iterations of the analysis.
- Have enough margin built into the test schedule to cope with unknowns and unexpected side effects of the tests. This is likely not news for anyone involved in spacecraft operations, but it is particularly relevant for such a mission phase as we tend to operate the spacecraft in new regimes after a typically long routine operations phase.
- When starting to plan this phase of the mission, try to collect information from past missions with similar profiles and missions that share, or carry similar, subsystems. Space systems are, understandably, built with margins. In this phase of the mission, one typically tends to operate some of the systems outside their acceptance and/or qualification boundaries – this is typically the case for the propulsion subsystem. It is useful to have flight data from previous missions at hand to inform some of the decisions during this phase of the mission.
- In line with the previous bullet point, make sure the experience gained by the team during this phase is preserved for future missions. Even if there is no established Long Term Data Preservation (LTDP) process at your organization, make sure to record the experience and findings and share with as many missions as possible.
- Design for disposal and passivation, making sure requirements for disposal and passivation are properly considered in the mission design phase.
- Last but not the least, make sure to engage the community that has grown around the mission to mark the day and celebrate the achievement. Just as important as the safe disposal and passivation of the spacecraft is the acknowledgement that this is also a personal milestone for many of the people that invested years (or decades) of their life in the design, development, operations and exploitation of the mission.

Acknowledgements

Mission operations for a complex space mission like Gaia is a team endeavour. The authors would like to thank the wider Gaia MOC team and subcontractors, the Gaia Project in ESTEC, the SOC and DPAC and Airbus Defence & Space and its industrial partners to the Gaia endeavour and this paper.

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