The Gaia project

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ICC/IEEC

IX RES, 23rd September 2015
Launch December 19 2013 09:12:19 UTC

- First 1h43m: First signal acquisition and automatic start-up sequence monitoring

- OK transmitter, gyroscopes, PLM bipod release, CPS priming, thermal control configuration

DSA deployment end 10:38 UTC
Gaia Calendar

- Gaia is the *Cornerstone Mission 6* in "Horizon 2000+" (ESA)

- Approved in 2001
- **2001-2003:** Phase A (feasibility studies)
- **2005-2006:** Phase B (detailed design)
- **2006-2013:** Phase C/D (construction)
- **19 Dec-2013:** Launch
- **July 2014 - 2018:** nominal operations (+1yr extension).
- Orbit around L2
- **2013-2022:** data reduction
Gaia’s main science goal is to unravel the dynamical and chemical evolution of the Galaxy – back in time to its formation – and to study its kinematics, dynamics, and structure.

A large 3D survey of the Milky Way (and beyond)

Based on Hipparcos principles (large angle, global astrometry) and success.

Hipparcos: launched Aug. 1989  
Operations: 1988 -1993  
Data reduction: 1988 -1997  
European leadership
Gaia capabilities

• Positions, proper motions and parallaxes for 1 billion stars (G < 20)

• Low resolution spectrophotometry for 1 billion stars, allowing estimations of Teff, logg, Av and [Fe/H]

• Radial velocities for 150 million stars (G < 16)

• Atmospheric parameters, reddening and rotational velocities for 5 million stars (G < 12)

• Detailed chemical abundances for 2 million stars (G < 11)
Scientific Goals
Two Challenges:

- **To build the satellite:**
  - Thermal and mechanical stability
    \[ \Rightarrow \text{CCDs operate at } \sim -110^\circ \text{C} \]
    \[ \Rightarrow <1 \text{mK at focal plane} \]
    \[ \Rightarrow \sim \mu \text{K in the torus} \]
  - High precision
  - The largest focal plane + TDI synchronized with rotation

- **Data processing:**
  - Complex relationship as astrometry, photometry and spectroscopy
  - \(~1\) PetaByte of data, \(10^{20-21}\) flop
  - \(\mu\)as accuracy, \(0.1 \mu\text{as} = 10^{-13}\) rad
  - Hipparcos approach (flat files, sequential process) not possible
Scan law
Telescopes, focal plane

106 CCDs, 938 million pixels, 2800 cm², 0.75 sqdeg
CCDs: 4500x1966 pix, operated in TDI mode

Sky Mapper CCDs
Astrometric Field CCDs

Image motion
Images courtesy EADS-Astrium
Windowing

N = 45 \times 10^6 \text{ obs/day}

Not all the pixels are readed

Window (in red): to be downloaded for each object detected and confirmed
Source detection/confirmation in action
Example:
- The required window around the star covers $18 \times 12$ CCD pixels
- The read window is composed of 18 along-scan samples of $1 \times 12$ pixels
- Only the 18 electron-count sample values are sent to the ground
Positions, G magnitude

(9 measures in each transit)
BP, RP Photometry

![Graphs showing photometric data for stars][1]

[1]: https://example.com/graphs.png
Spectrum, radial velocities
Data Analysis: Concept and Requirements

\[ R_i (s, a, c, g) = \eta^{obs} (t_i \mid c) - \eta^{calc} (t_i \mid s, a, g, \kappa) \]

- **Calibration parameters** (AL/AC positions of CCDs, etc)
- **Source parameters** \((\alpha_\odot, \delta_\odot, \pi_\odot, \mu_\odot, \nu_\odot)\)
- **Attitude parameters** (spline coefficients)
- **Auxiliary parameters** (e.g., Ephemeris)
- **Global parameters** (e.g., PPN \(\gamma\))
- **Time of observation** \(t_i\)
Astrometric solution

Estimates parameters of 4 models:

- S Source: $5 \times 10^9$ param
- A Attitude: $\sim 10^8$ param
- C Calibration: $\sim 10^6$ param
- G Global: $< 10^2$ param

$$\min_{s, a, c, g} \sum_l \left[ \frac{t_l - f_l(s, a, c, g)}{\sigma_l} \right]^2$$

- Least squares solution: $10^{10}$ parameters using $10^{12}$ observations,
- direct solution unfeasible (Bombrun et al. 2011),
- use Astrometric Global Iterative Solution: AGIS (Lindegren et al. 2012)
Astrometric Global Iterative Solution

- 100 million stars
- Model for secondary stars
- Not fitting to the model: CUx
- Improved after new data are available => Data Updating

Figure 1: Functional overview of AGIS processes and top-level data flow
Intermediate Data Update

- Inner iteration: (non-linearity and outliers)
- AGIS iteration: (S-A-C-G cross-terms)
- Outer iteration: (interaction with all other processes)

- New transit data
- Improved centroids
- Improved selection of primary sources
The final responsibility of the Mission is in the hands of ESA.

Data reduction is a responsibility of the scientific community, funded by the member states.
Data Processing and Analysis Consortium (DPAC)

- 459 members
- 24 Funding Agencies

MLA duration: 2007–2022
FTEs/year up to 2011: 270
Average yearly cost: ~30Meuros
Global cost: ~500M€

With a 5 years mission, ~33% of DPAC cost will be dedicated to Operations.
Data collection and distribution
Tasks at BSC (I)

- Simulations for testing the whole Gaia-DPAC processing chain:
  - High-realism simulation of the Gaia instrument - GASS
  - High-realism simulation of the Gaia catalogue - GOG

- Provision of:
  - Full-scale sky simulations for Operations Rehearsals – testing of the main Scientific Critical software involved in the daily processing of Gaia Telemetry stream.
  - Reduced density simulations covering long term periods for the testing of the whole Gaia data processing chain
Achieved Milestones

Scientific milestones:

- Large mission simulations using realistic Universe Model
- Simulation of telemetry for rehearsal campaigns before Gaia launch
- 1.2 billions sources catalogue
- Simulation of epoch and combined (final) data using GOG
- Simulations of RVS (spectra) data
Gaia Simulations

Density of stars in the Milky Way at different magnitude (1000 million objects simulated)
Achieved Milestones

Computational Products:

- **GASS** (telemetry simulation)
  - >20 datasets, from few days to 5 years at reduced density
  - 4 Operational rehearsal dataset (several days of full density telemetry).
  - Several TB of data generated

- **GOG** (object generator)
  - 2 full sky simulations
  - >30 datasets (special objects, partial sky, etc)
  - Several TB of data generated
Tasks at BSC (II)

- Raw data re-processing and calibration system – Intermediate Data Updating (IDU)
- Detailed design and first implementation
- Assessed feasibility of concept and correct integration in the whole Gaia processing chain
- Test on 1.5 years of downsized data (700M observations, equiv. 8 days mission) in just 5 days using up to 84 MareNostrum II nodes
- Running some IDU-processes on real data (XM, Detection Classifier)
Data products

Gaia raw data re-processing system (IDU)

Determination of the along-scan and across-scan positions of the observations
Data at DPCB

<table>
<thead>
<tr>
<th>Month</th>
<th>Files received</th>
<th>Size (GB)</th>
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<tbody>
<tr>
<td>2013-10</td>
<td>5</td>
<td>122.00</td>
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<tr>
<td>2013-12</td>
<td>776</td>
<td>4.57</td>
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<tr>
<td>2014-01</td>
<td>9332</td>
<td>37.04</td>
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<td>2014-02</td>
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<td>2014-03</td>
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<td>2014-04</td>
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<td>2014-06</td>
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<td>2014-07</td>
<td>104357</td>
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<td>2014-08</td>
<td>119372</td>
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<td>2014-09</td>
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<td>2014-12</td>
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<td>2015-06</td>
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<td>2015-07</td>
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<td>1090.00</td>
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<tr>
<td>2015-08</td>
<td>211013</td>
<td>1280.21</td>
</tr>
</tbody>
</table>

AstroObservations (AO) in operations:
Total size: 10,417 GB
AO received by time (4 days)
AO received by time (10 months)
Accumulated AO during (10 months)
Detection Classifier
Hipparcos 50717

Without filtering spurious detections

Filtering spurious detections
Hipparcos 21421

Without filtering spurious detections

Filtering spurious detections
Extended objects
Cat's Eye Nebula. NGC6543
Pinwheel Galaxy, NGC5457
Cross-matching observations

1. Objects are matched in successive scans
2. Attitude and calibrations are updated
3. Objects positions etc are solved
4. Higher terms are solved
5. More scans are added
6. System is iterated

Sky scans (highest accuracy along scan)

Scan width: 0.7°
XM resolution is currently under heavy development to improve handling of complex cases. This will most likely lead to higher CPU requirements.
After 11 months of Nominal Operations:

Nominal mission time: 340 days

Raw data received: ~9 TB (~26GB/day)

Astro/photometric transits received: > 22 billion (~64M/day)

Astrometric CCD measurements: > 220 billion

Photometric CCD measurements: > 44 billion

Spectroscopic transits received: > 1.5 billion (~4.5M/day)

Spectroscopic CCD measurements: > 4.5 billion

Main DB size: ~70 TB
# Data release scenario

<table>
<thead>
<tr>
<th>First release:</th>
<th>Positions ((\alpha, \delta)) and G-mag for single-like stars (90% of the sky)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ecliptic pole data during commissioning</td>
</tr>
<tr>
<td></td>
<td>the Hundred Thousand Proper Motions (HTPM) catalogue based on the Hipparcos stars → Tycho-Gaia (TGAS)?</td>
</tr>
<tr>
<td>Second release:</td>
<td>Positions, proper motions, parallaxes and G-mag (90% of the sky)</td>
</tr>
<tr>
<td></td>
<td>Integrated XP photometry for sources with Astrophysical parameters estimated with appropriate standard errors.</td>
</tr>
<tr>
<td></td>
<td>Mean radial velocities for stars with non-variable radial velocity (90% of the sky)</td>
</tr>
<tr>
<td>Third release:</td>
<td>Astrometric solutions + radial velocity + orbital solutions for binaries (2 months – 75% of the observing time)</td>
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<tr>
<td></td>
<td>Object classification and astrophysical parameters, together with XP and RVS spectra for well-behaved objects.</td>
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<tr>
<td></td>
<td>Mean radial velocities and atmospheric parameter estimates for non-variable stars.</td>
</tr>
<tr>
<td>Fourth release:</td>
<td>Variable star classifications and parameters as available, and the epoch photometry</td>
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<tr>
<td></td>
<td>Solar system results with preliminary orbital solutions and individual epoch observations</td>
</tr>
<tr>
<td></td>
<td>Non-single star catalogue</td>
</tr>
<tr>
<td>Final release:</td>
<td>Full astrometric, photometric, radial velocity catalogue</td>
</tr>
<tr>
<td></td>
<td>All available variables and non-single stars solutions</td>
</tr>
<tr>
<td></td>
<td>Source classifications (probabilities) + multiple astrophysical parameters derived from BP/RP, RVS and astrometry for stars, unresolved binaries, galaxies and quasars. Some parameters may not be available for faint(er) stars.</td>
</tr>
<tr>
<td></td>
<td>List of exoplanets.</td>
</tr>
<tr>
<td></td>
<td>All epoch and transit data for all sources</td>
</tr>
<tr>
<td></td>
<td>All Ground Based Observations made for data processing purposes (or links to it)</td>
</tr>
</tbody>
</table>

[http://www.cosmos.esa.int/web/gaia/release](http://www.cosmos.esa.int/web/gaia/release)
Tycho Gaia Astrometric Solution (TGAS)

- Tycho: 2.5 millions stars
- 6 – 12 month of Gaia observations: two parameters
- Sub-mas accuracy for positions, pm parallaxes
Conclusions

- Gaia operating nominally around L2 with all the instruments
- Ground-segment working (reception, input data)
- DPAC daily systems working. Almost all the systems running
- BSC. IDU runs started. Full IDU execution beg. 2016
  Simulator activities finished
- Added complexity due to “instrumental” problems
- Calibrations and BAM under analysis (also adding complexity)
- First data release + TGAS in mid 2016
Gravitational lensing detected by Gaia placed over HST images. QSOs are very distant ($10^9$ ly). Lensing produced by a galaxy some 100 Mpc away. Astrometric accuracy $< 100$ mas.