Gaia Mission Summary

G. Sarri / T. Paulsen (Gaia Project Office)
May 2013
Gaia is a cornerstone of the ESA science programme
Evolution of astrometric accuracy

- Hipparchus: 1000 stars
- The Landgrave of Hessen: 1000
- Tycho Brahe: 1000
- Flamsteed: 4000
- Argelander: 26000
- Bessel: 1 star
- Jenkins: 6000
- FK5: 1500
- USNO: 100
- PPM: 400 000
- Tycho: 1 million
- UCAC2: 58 million
- Hipparcos: 120 000
- Gaia: 1000 million

Errors of best star positions and parallaxes

Year: 150 BC to 2000

Arcsec: 1000 to 0.00001
Gaia mission objectives

- To create the largest and most precise 3D chart of our Galaxy by providing positional and velocity measurements for about one billion stars

- Astrometry and Photometry for at least one billion stars (1% of the stars in the Milky Way)

- Spectroscopy for about 150 million stars

- One billion objects observed on the average 70 times over 5 years mission is 40 million stars a day (400 million measurements a day)

- Order of magnitudes improvement w.r.t. Hipparcos
From Hipparcos to Gaia

<table>
<thead>
<tr>
<th></th>
<th>Hipparcos</th>
<th>GAIA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnitude limit</strong></td>
<td>12 mag</td>
<td>20 mag</td>
</tr>
<tr>
<td><strong>Completeness</strong></td>
<td>7.3 – 9.0</td>
<td>~20 mag</td>
</tr>
<tr>
<td><strong>Bright limit</strong></td>
<td>~0</td>
<td>~3-7 mag</td>
</tr>
<tr>
<td><strong>Number of objects</strong></td>
<td>120 000</td>
<td>26 million to V = 15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>250 million to V = 18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000 million to V = 20</td>
</tr>
<tr>
<td><strong>Effective distance limit</strong></td>
<td>1 kpc</td>
<td>1 Mpc</td>
</tr>
<tr>
<td><strong>Quasars</strong></td>
<td>None</td>
<td>~5 x 10^5</td>
</tr>
<tr>
<td><strong>Galaxies</strong></td>
<td>None</td>
<td>10^6 - 10^7</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td>~1 milliarcsec</td>
<td>7 μarcsec at V = 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12-25 μarcsec at V = 15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200-300 μarcsec at V = 20</td>
</tr>
<tr>
<td><strong>Broad band</strong></td>
<td>2-colour (B and V)</td>
<td>5-colour to V = 20</td>
</tr>
<tr>
<td><strong>Medium band</strong></td>
<td>None</td>
<td>11-colour to V = 20</td>
</tr>
<tr>
<td><strong>Radial velocity</strong></td>
<td>None</td>
<td>1-10 km/s to V = 16-17</td>
</tr>
<tr>
<td><strong>Observing programme</strong></td>
<td>Pre-selected</td>
<td>Complete and unbiased</td>
</tr>
</tbody>
</table>
Gaia science performances

End of mission astrometry performances

<table>
<thead>
<tr>
<th>Band</th>
<th>EOM Performance [mmag]</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1V</td>
<td>5</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>G2V</td>
<td>5</td>
<td>&lt; 8</td>
</tr>
<tr>
<td>M6V</td>
<td>8</td>
<td>&lt; 20</td>
</tr>
</tbody>
</table>

End of mission photometry performances

<table>
<thead>
<tr>
<th>Band</th>
<th>EOM Performance [mmag]</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1V</td>
<td>6</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>G2V</td>
<td>5</td>
<td>&lt; 8</td>
</tr>
<tr>
<td>M6V</td>
<td>6</td>
<td>&lt; 10</td>
</tr>
</tbody>
</table>

End of mission radial velocity spectroscopy performances

<table>
<thead>
<tr>
<th>V mag</th>
<th>EOM Performance [km/sec]</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1V</td>
<td>0.6</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>G2V</td>
<td>8.5</td>
<td>&lt; 15</td>
</tr>
<tr>
<td>K1IIIMP</td>
<td>13.3</td>
<td>&lt; 15</td>
</tr>
</tbody>
</table>

G. Sarri / T. Paulsen | Gaia_Mission_Summary_May_2013 | Slide 7
Launch and operations

Orbit determination accuracy:
- position < 150 m
- velocity < 2.5 mm/s
Sky-Scanning Principle

Spin axis: 45° to Sun
Scan rate: 60 arcsec s⁻¹
Spin period: 6 hours

This revolving scanning:

- keeps the viewing directions at a constant angle to the sun (thermal)
- provides a fairly uniform coverage of the sky
- allows the details of the star motion to be identified
Elements of the Gaia program

Satellite

Cebreros

New Norcia

Launcher

Data Processing & Analysis Centre (DPAC)

Mission Operation Centre (MOC)

ESOC

Science Operation Centre (SOC)

ESAC
Short program history

- Gaia SPC approval, Oct 2000
- Dec 2002, start of definition
- Definition Phase A/B1
- July 1st 2005, ITT to industry
- March 1st 2006, kick-off Phase B2/C/D
- Phase B2
- July 7th 2006, SRR
- June 29th 2007, PDR
- Phase C/D
- Oct 15th 2010, CDR
- Apr 13th 2011, Mission CDR
- July 2013, FAR
- Sept 19th, 2013, Launch
- Commissioning
  - Jan 2014, IOC
- Nominal operations (5 y)
- Extended operations (1 y)
- Jan 2020, End of Mission
Overview of the spacecraft

- **Mass**
  - S/C wet launch mass 2030 kg
  - Bi-propellant fuel 335 kg
  - Cold gas fuel 60 kg

- **Power**
  - 1.9 kW

- **Data management**
  - Data rate up to 7.5 Mbps
  - Data storage 1 Terabit
  - Atomic clock 1 s drift in 250000 y

- **Optical payload**
  - Two telescopes
  - Entrance pupil 1.45 x 0.5 m²
  - Focal length 35 m
  - Field of View 1.58 x 0.69 deg
  - Focal plane size 1 Gpixels
Gaia Service Module (SVM)
Gaia Payload Module (PLM)
Focal Plane Assembly (FPA)
The core of the detection: CCD

<table>
<thead>
<tr>
<th>CCD dimensions</th>
<th>1 pixel AL</th>
<th>45 mm AL</th>
<th>10 µm</th>
<th>0.074 deg</th>
<th>0.097 deg</th>
<th>0.982 ms</th>
<th>4.42 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 pixel AL</td>
<td>10 µm</td>
<td>0.059 arcsec</td>
<td>0.982 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 pixel AC</td>
<td>30 µm</td>
<td>0.177 arcsec</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4500 pixels AL</td>
<td>45 mm</td>
<td>0.074 deg</td>
<td>4.42 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1966 pixels AC</td>
<td>59 mm</td>
<td>0.097 deg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Two viewing directions

Figure 4. Illustrating the principle of absolute parallax measurement: in the left diagram, the measurement of the (small) angles A, B only allows to determine the relative parallax \( \pi_1 - \pi_0 = (A - B)/2 \). By contrast, measuring the large angles in the right diagram allows to obtain the absolute parallax \( \pi_1 = (A - B)/2 \) independent of the distance to the reference star.
Telescopes and mirrors
Phased Array Antenna (PAA)
Gaia will be carried into space by a Soyuz-STB launch vehicle with a Fregat MT upper stage.

Launch site is the CSG in French Guiana.
Data Processing / Reduction

If we had simply dumped all the CCD data to ground (every pixel) we would end up with \( \sim 73000 \) TB after 5.5 years mission!

The immense volume of data created by Gaia:

\[ 50\text{GB/Day} = 100\text{ TB} (65\text{ TB Astro + Photometer, 35 TB RVS}) \]

and their complex relationships make the data processing requirements amongst the most challenging even by the standards of computational power in the next decade.

The required numerical processing (core processing) is of the order of \( 10^{21} \) floating-point operations.

To meet this challenge, the Gaia Data Processing and Analysis Consortium (DPAC) organises nearly 450 scientists and software engineers in nine Coordination Units (CU), 25 countries, currently designing and implementing a software system (distributed over several processing centres) for analysing the data when it starts arriving in 2013, and simulating telemetry data before launch.
A huge ground data processing effort

- **Data volume**
  - compressed telemetry: 250 Tbit
  - raw data: 100 TByte
  - processed data and archives: 0.5-1 PByte

- **Computational size**
  - $1.5 \times 10^{21}$ FLOP
  - 10 TFLOP/s $\rightarrow$ 2 years CPU

---

**Signal formation and recording**

**True**

\[
\alpha, \delta, \mu_{\alpha}, \mu_{\delta}, \sigma, V_r, G, B - V
\]

**Estimated**

\[
\alpha, \delta, \mu_{\alpha}, \mu_{\delta}, \sigma, V_r, G, B - V
\]

**Signal analysis and processing**

**Input data**

Gaia Mission Components

- **Space segment**: The satellite
- **Operation ground segment**: ground stations and Mission Operation Centre (MOC)
- **Science ground segment**: Science Operation Centre (SOC) and Data Processing (DPAC)

![Diagram of Gaia Mission Components](image)

- ESOC in Darmstadt
- ESAC
- New Norcia, Perth, Australia
- Cebreros, Ávila, Spain
- X-band < 8.7Mbps
Data Processing Task

1. **TM**
   - Telemetry (raw) data

2. **FL**
   - First Look
     - photon counts (etc.)

3. **Raw database**

4. **IDT**
   - Initial Data Treatment
     - elementary observations (etc.)
     - Updated in 6 months cycles

5. **IDU**
   - Intermediate Data Update

6. **Main database**

7. **AGIS:**
   - Source Attitude Calibration Global
AGIS Iterations

The sky charts show results from recent AGIS runs using simulated data for $10^6$ stars. Initial errors of up to 0.1 arcsec (left) were brought down to the 10 μas level after 48 AGIS iterations (centre and right).

The remaining error patterns show eigenvectors of the iteration matrix and will largely disappear with further iterations. This property can be used to improve the convergence rate of AGIS.

Improved Accuracy with time
• Determining the positions, distances, and annual proper motions of >1 billion stars with an accuracy of about 20 µas (microarcsecond) at 15 mag, and 200 µas at 20 mag
• Determining the radial velocity measurements with expected detection of tens of thousands of extra-solar planetary systems
• Capacity to discover Apohele asteroids with orbits that lie between Earth and the Sun, a region that is difficult for Earth-based telescopes to monitor since this region is only in the sky during or near the daytime.
• Detection of up to 500 000 distant quasars
• More accurate tests of Albert Einstein’s general relativity theory
• Data-distribution policy:
  – final catalogue ~2021
  – intermediate catalogues currently under definition
  – science-alerts data released immediately
  – no proprietary data rights