The Astrometry Satellite Gaia

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Gaia’s schedule

- **1993**: First proposal to ESA
- **2000**: accepted as „Cornerstone Mission“
- **Launch**: December 19, 2013
- **End of commissioning**: July 18, 2014
- **September 14, 2016, 12:30 CEST**: Gaia DR1
- **April 2018**: Gaia DR2
- **2019**: End of nominal measurements (5 years)
- **2022/2023**: Publication of final catalogue?
- Estimated end of mission due to cold gas exhaustion end-2023 ±1 year
The Launch

- Soyuz-Fregat
  - 47 m high
  - Sinnamary in French Guyana
  - Launch date: 19. Dezember 2013
Gaia at L2

Animation with Gaia Sky:
Toni Sagristà Sellés
(ARI/ZAH University of Heidelberg)
Software downloadable at
https://zah.uni-heidelberg.de/gaia/outreach/gaiasky/
Gaia’s main goals

The determination of positions, movements and parallaxes (distances) of 1 billion stars

This means (practically) all stars down to magnitude 20.7
(equivalent to the brightness of a candle at 30000 km distance)
History of Parallax Measurements

Number of significant parallaxes:

- 1838: 1
- 1900: 100
- 1990: 900
- 1997: 50,000
- Since September 14, 2016: 600,000 von Gaia
- And many more to come in April 2018 and thereafter...
Parallaxes are small

\[
\frac{\sigma}{\pi} = 0.1\% \quad d = 40 \text{ pc}
\]

\[
\frac{\sigma}{\pi} = 1\% \quad d = 400 \text{ pc}
\]

\[
\frac{\sigma}{\pi} = 10\% \quad d = 4 \text{ kpc}
\]

\[\sigma = 25\mu\text{as}\]

\[\text{at } V = 15\]
Scanning, Focal plane
How do stars move? 5 parameters

- **Position at reference epoch** ($\alpha_0, \delta_0$)
- **Proper motion** ($\mu_\alpha, \mu_\delta$)
- **Parallax** ($\varpi$)
- **Path of star on the sky**
Gaia’s data reduction problem

With the same accuracy with which Gaia
• measures position of stars,
it is necessary to know
• where Gaia is pointing at (attitude), where Gaia is, how fast it is,
how exactly
• the optic and detectors are aligned
• and, whether Einstein was fully right!!
Astrometric data reduction

- $10^{12}$ individual measurements
- $<10^{10}$ unknowns
- The unknowns are strongly correlated with each other

- 5000 million astrometric parameters
- 150 million unknowns for the attitude
- 10-50 million other calibration parameters
From raw data to catalogue

Credit: Uwe Lammers ESA Science Team, 2010
Gaia DR1 content (Sep 14, 2016)

- Billion star atlas ($G \leq 20.7$)
- Positions and magnitudes for $\sim 2000$ ICRF quasars
- Tycho-Gaia Astrometric Solution ($\sim 2$ million, $G \leq 12$)
- Variable stars near south ecliptic pole ($\sim 600$ Cepheids, $\sim 2600$ RR Lyrae)

A. Brown
Observations over 5 yr ⇒ pos, par, p.m.

from Lammers et al.
Degeneracy for less than 1 year

from Lammers et al.
Degeneracy for less than 1 year

Michalik & Lindegren

Coordinate, e.g., δ(t)

0 1 2 3 4 5
Time [yr]
Observation of less than one year plus one old position

\[ \Rightarrow \text{Independent long-baseline proper motions, parallaxes} \]
Number of sources and parameters in Gaia DR1

<table>
<thead>
<tr>
<th>Solution</th>
<th>No. of sources</th>
<th>Param.</th>
<th>Prior used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary (TGAS) sources</td>
<td>2,057,050</td>
<td>5</td>
<td>positions at 1991.25</td>
</tr>
<tr>
<td>- of which Hipparcos</td>
<td>93,635</td>
<td>5</td>
<td>- Hipparcos positions</td>
</tr>
<tr>
<td>- of which Tycho-2 (excl Hipp)</td>
<td>1,963,415</td>
<td>5</td>
<td>- Tycho-2 positions</td>
</tr>
<tr>
<td>Secondary sources</td>
<td>1,140,622,719</td>
<td>2</td>
<td>$\varpi, \mu_{\alpha^*}, \mu_\delta = 0 \pm \text{few mas/yr}$</td>
</tr>
<tr>
<td>ICRF sources (*) = QSOs</td>
<td>2,191</td>
<td>2</td>
<td>$\mu_{\alpha^*}, \mu_\delta = 0 \pm 0.01 \text{mas/yr}$</td>
</tr>
<tr>
<td>All</td>
<td>1,142,679,880</td>
<td></td>
<td>$d(\mu_{\alpha^*}, \mu_\delta)/dt = 0$, i.e. $v_r = 0$</td>
</tr>
</tbody>
</table>

(*) 2080 of the ICRF sources are also secondary sources (with slightly different positions)
Improved distances to nearby stars

Hipparcos

Gaia DR1 (TGAS)

L. Lindegren
More stars within parallax horizon ($\varpi/\sigma_\varpi > 5$)

Hipparcos

Gaia DR1 (TGAS)

Sun

L. Lindegren

Stefan Jordan

ARI, Zentrum für Astronomie, Uni Heidelberg
Source density map of Gaia DR1
Primary (TGAS) sources

2.06 M sources, mainly G < 11.5
• this is about 80% of the Hipparcos & Tycho-2 catalogues

Missing sources:
• brights stars (G < 6)
• high-proper motion stars (μ > 3.5 "/yr)
• some 20% of Hip + Tycho-2 with too few observations (quasi-random but with large variations over the sky)

Median position uncertainty: 0.23 mas at 2015.0
Median parallax uncertainty: 0.32 mas
Median proper motion uncertainty:
• 0.07 mas/yr (Hipparcos subset)
• 1.2 mas/yr (Tycho-2 subset)

Note difference!

L. Lindegren
Systematics in Gaia DR1 parallaxes

- Due to known limitations in the astrometric processing
  - a global offset of ±0.1 mas may be present
  - there are colour dependent, spatially correlated errors of ±0.2 mas
  - over large spatial scales, parallax zero point errors reach ±0.3 mas
  - in a few very small areas even ±1 mas (is indicated)

- Parallax uncertainties in restricted areas of the sky should be quoted as
  \[ \varpi \pm \sigma_{\varpi} \] (random) ± 0.3 mas (syst.)

- Averaging parallaxes e.g. in a cluster does not reduce the systematics!

L. Lindegren
DR1- Parallax uncertainty

- Median parallax uncertainty ~ 0.3 mas
- Parallax systematics at 0.3 mas level
- Errors levels partly reflect early scanning law coverage and geometry

Cell size: 0.84 deg²

Credits: DPAC-CU3 team
DR1- TGAS median proper motion uncertainty

- Median proper motion uncertainty $\approx 1.3 \text{ mas yr}^{-1}$
- Also about $0.3 \text{ mas yr}^{-1}$ systematic error!
• Median proper motion uncertainty ≈ 0.07 mas yr$^{-1}$
• <0.1 mas yr$^{-1}$ systematic error!
Blue and Red Photometer

\[ \frac{\lambda}{\Delta\lambda} < 100 \]
Field of view  RVS Spektrograph  CCD detector

Single RVS spectrum of K5 star HIP 86563 (V=6.63) compared to a ground-based spectrum

\[ \Delta\lambda/\lambda = 11500 \]
Status of measurements until Oct 24, 2017

- **Days in nominal mission**: 1187
- **Astrometric measurements**: 858 billion
  - G<20.7 mag
  - Bright limit around G=2-3 mag
  - All bright stars imaged (G<3 mag) (Gaia SM)
- **Photometric measurements**: 174 billion
  - 330-680 nm BP
  - 640-1050 nm RP
- **Photometry in G-band on astrometric detectors**
- **Spectroscopic measurements**: 16 billion
  - G_{RVS}<16.2 mag
    - 845-872 nm with R about 11,000
- **Radial Velocity Spectrometer for >100 million radial velocities**
- **Bright limit around G=2-3 mag**
Excessive Straylight

- Diffracted sunlight
- Milky Way
- Bright point objects

1. Sunshield
2. Insufficient baffling
Excessive Straylight

- Diffracted sunlight
- Milky Way
- Bright point objects

1. Sunshield
2. Insufficient baffling
Contamination

CU5/DPCI team
Cyclic Variation of the Basic Angle

- The basic angle varies with a period of 6 hours = rotation with respect to the Sun
- Amplitude: 1.1 milliarcseconds
- Specification: 4 microarcseconds
- Corresponds to a shift of only a few nanometers

1 mas = $5 \times 10^{-9}$ rad < 4 nm
movement of the main-mirror edges ~ 10 Si atoms

(and even much less if it is a different mirror)
Noise: a dozen or so picometers!
Apparent scan rate variations

Micro-clanks!
Very first science

Arrows: TGAS proper motion variation of HIP stars
Background: Gaia source density

van der Marel & Sahlmann 2016

Gaia LMC

A. Brown
190 Papers published on DR1

- [http://adsabs.harvard.edu/cgi-bin/nph-abs_connect?library&libname=Gaia+DR1&libid=58e66b71f4](http://adsabs.harvard.edu/cgi-bin/nph-abs_connect?library&libname=Gaia+DR1&libid=58e66b71f4)
Fundamental Physics with Gaia
Gaia and Dark Matter

- The only way we’ve detected dark matter is through its gravitational effects.
- We can find the dark matter density by finding the gravitational potential (and subtracting off the baryonic contribution).

\[ \nabla^2 \Phi = 4\pi G \left( \rho_b + \rho_{DM} \right) \]
Gaia and Dark Matter

Rotation curve of our Milky Way

Sofue 2009
Gaia and Dark Matter

Fit with different components

Pranzos et al. 2010
Gaia and Dark Matter

Where can Gaia help?

• Solar neighbourhood:
  – Precise rotation curves
  – Local volume density
    • DM contribution
    • Now: Baryonic contribution uncertain by 10% ➔ DM uncertain by 100%

• Scale height

• Precise parallaxes not influenced by interstellar extinction ➔ better scale length of Galaxy (mass determination)

• Stellar Streams
Stellar Streams probe the Galactic potential

- Precise parallaxes and proper motion
- Stellar streams probe the galactic potential also in the halo
- Oblateness of DM halo
- Clumpiness of DM halo
Improvement of Hubble constant with Gaia

Velocity-Distance Relation among Extra-Galactic Nebulae.

"velocity = Hubble constant * distance"
Improvement of Hubble constant with Gaia

Three Steps to Measuring the Expansion Rate of the Universe

Galaxies hosting Cepheids and Type Ia supernovae

Distant galaxies in the expanding universe hosting Type Ia supernovae

Light redshifted (stretched) by expansion of space

100 Million – 1 Billion Light-years

6 – 18 K CMB
A test of Gaia Data Release 1 parallaxes: implications for the local distance scale
Stefano Casertano, Adam G. Riess, Beatrice Bucciarelli, Mario G. Lattanzi

- Comparison of 212 Cepheide distances with current calibration with Gaia parallaxes
- DR1 parallaxes fit very well
- Gaia error overestimated by about 20%.
- If one trust the Gaia parallaxes fully: Hubble constant about 0.3% smaller than previously known.
- Gaia parallax zero point known better than ~20 μas.
- Full mission will allow measurement of better than 1%
Improvement of Hubble constant with Gaia

$H_0 = 73.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$

(Gaia DR1)

The Planck Collaboration (2016): value of $66.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$

Difference of $2.5-3.5\sigma$
Gaia Relativity Model

Astrometry

Model

Relativity

Klioner
Light deflections at the sun

Actual position of star

Apparent position of star

(maximum: 1.75 arc seconds = 100000 time Gaia’s accuracy)

Perpendicular to the sun:
4 milli arc seconds
= 200 times Gaia’s accuracy
Gaia Relativity Model

- Relativistic model for astrometric observations (Klioner 2003, 2004):
  - aberration via Lorentz transformations
  - deflection of light: monopole (post- und post-post-Newtonian), quadrupole and gravitomagnetic terms
  - up to 17 bodies routinely, more if needed
    - relativistic definitions of parallax, proper motion, etc.
    - relativistic definitions of observables and the attitude of the satellite
    - relativistic model for the synchronization of the Gaia atomic clock and ground-based time scale (Gaia proper time etc.)

- Accuracy: 0.1 μas (at a distance larger than a few degrees from the Sun). Gaia observes at distances > 45°

Klioner
Gaia Relativity Model

- $s$: the observed direction
- $n$: tangential to the light ray at the moment of observation
- $\sigma$: tangential to the light ray at $t = -\infty$
- $k$: the coordinate direction from the source to the observer
- $l$: the coordinate direction from the barycentre to the source
- $\bar{\omega}$: the parallax of the source in the BCRS

Accuracy limit: 0.1 μas (at a distance larger than a few degrees from the Sun)
Light deflection by Planets

The sky from L2 in 'ecliptic' coordinates at JD2455562.5 = 2011-Jan-01

Light bending in microarcsec

ESA/Jos de Bruijne
Perihelion precession

- 200-300,000 asteroids
- Several with large orbital eccentricities
- Disentangle solar quadrupole moment

\[
\Delta \omega = \Delta \omega_{PPN} + \Delta \omega_{J2}
= \left[ \frac{6\pi m_{\odot}}{a^{5/2}(1-e^2)} \Gamma + \frac{6\pi R_{\odot}^2}{4a^7/2(1-e^2)^2} \frac{5\cos^2i - 1}{J_2} \right] (t-t_0)
= \frac{3m_{\odot}}{a(1-e^2)} \left[ \Gamma + \frac{R_{\odot}^2}{4am_{\odot}} \frac{5\cos^2i - 1}{(1-e^2)} J_2 \right] n(t-t_0),
\]

From Hestroffer et al. 2010
Perihelion precession

- 200-300,000 asteroids
- Several with large orbital eccentricities
- Disentangle solar quadrupole moment

\[ \delta \varpi : \begin{array}{ll}
\text{GR} & \text{mas/yr} \\
\text{J}_2(=10^{-7}) & \text{mas/yr} \\
\hline
\text{Mercury} & 430 & 0.124 \\
\text{main belt} & a = 2.70 \text{ AU} & e = 0.1 & 3.4 & 0.0001 \\
3200 \text{ Phaethon} & a = 1.27 \text{ AU} & e = 0.83 & 102 & 0.040 \\
1566 \text{ Icarus} & a = 1.08 \text{ AU} & e = 0.83 & 101 & 0.030 \\
5786 \text{ Talos} & a = 1.08 \text{ AU} & e = 0.82 & 101 & 0.030 \\
\end{array} \]

From M.T. Crosta and F. Mignard
Gaia Relativity Model

Each relativistic effect used in the models can be used to test GR

Klioner
Gravitational waves and astrometry

- At each moment of time a GW produces a deflection pattern on the sky: it is not a pure quadrupole, but rather close to it (Braginsky et al, 1991; Pyne et al, 2006; Gwinn et al, 2006; Book, Flanagan, 2011; Klioner, 2014-)

This is for a GW propagating in the direction $\delta=90^\circ$ ("+" polarization)
Low-frequency GWs

If the frequency of the GW is large enough, the time-dependence of the deflection does not allow the effect to be absorbed by proper motion. This is now a time-dependent pattern in the residuals of the solution (at each moment of time only certain directions are observed):

2. Maximal theoretical sensitivity of Gaia to a constant parameter

$$\sigma_h \geq \left( W_{\text{full}} \right)^{-1/2} = 5.4 \times 10^{-4} \mu\text{as} = 2.6 \times 10^{-15}$$

The actual sensitivity is at least a factor 10-100 worse (Geyer, Klioner, 2014-)

Systematic errors can significantly decrease the sensitivity (at all frequencies)
Low-frequency GWs

If the frequency of the GW is large enough, the time-dependence of the deflection does not allow the effect to be absorbed by proper motion.

This is now a time-dependent pattern in the residuals of the solution (at each moment of time only certain directions are observed):

1. The frequency that could be detected in Gaia data

\[ 3 \times 10^{-9} \text{ Hz} < \nu < 3 \times 10^{-5} \text{ Hz} \]

not too much correlated to proper motions

slower than 1.5 periods of rotation

Sensitivity is flat in “h” over the whole frequency range!

No systematic errors of Gaia are currently known that could influence this behavior…

Klioner
Gaia extension

- Nominal Gaia mission ends mid-2019 after 5 years of measurements
- Hardware and operations designed for a 5-year survey for sky homogeneity
- Scientifically the best option is to start a new 5-year survey on top of the nominal 5-year survey

Notes on continued S/C operations
- All hardware in good shape
- Only limiting factor is micro-propulsion system fuel
- Estimated to run out by mid 2024

A. Brown
Improvement of scientific performance

- Basic mission results improve with $t^{-0.5}$
  - Positions, parallaxes, photometry and radial velocities

- Rapidly increasing gain in kinematics and dynamics
  - Proper motion improvement scales as $t^{-1.5}$
  - More complex systems scale faster, e.g. improvement in unambiguous determination of orbital period,
  - mass and distance of a perturbing body scales as $t^{-4.5}$

<table>
<thead>
<tr>
<th>Improvement factor for mission length increase from 5 to 10 years</th>
<th>Distance increase at the same accuracy</th>
<th>Volume increase at the same accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallax</td>
<td>1.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Proper motion</td>
<td>2.8</td>
<td>23</td>
</tr>
</tbody>
</table>

A. Brown
Improvement for stars and stellar clusters

- Factor ~ 8 more clusters
- Reach inner and Perseus spiral arms
- Reach larger diversity of environments and cluster types
- Probe low stellar masses at larger distances

A. Brown
Improvement for MW and stellar populations

- Larger volume reached throughout the halo at given proper motion accuracy
- Tidal streams detection improvement
- Probe young and unmixed debris located beyond 20–30 kpc
- Calibration of photometric distance indicators on nearby samples ⇒ full gain in tangential motion performance
What can be expected from Gaia DR2?

- Will be completely independent of Hipparcos/Tycho-2
- Based on a longer stretch of data (22 versus 14 months)
- Improved attitude and instrument models will reduce the modelling errors and hence both random and systematic errors in results
- Parallax accuracies of about 50 μas can be reached for sources down to G ~ 15 mag, larger errors for fainter sources
- Proper motions of about 100 μas yr\(^{-1}\) (comparable to the Hipparcos subset of TGAS) down to G ~ 15 mag
- This will be obtained for many tens of millions of sources
- Improved and more photometry (G, BP, RP) will enhance the scientific usefulness enormously
- Gaia DR1 is a good training set to get prepared for the real thing!
Teamwork to deliver the promise of Gaia

- 10+ years of effort
- 450 scientists and engineers
- 160 institutes
- 24 countries and ESA
- Six data processing centres
Gaia Sky Flight
APOD: Here comes the Sun

Stefan Jordan
ARI, Zentrum für Astronomie, Uni Heidelberg

656th WE-Haerens Seminar,
Fundamental Physics in Space, October 23-27, 2017
Stamps to be published by German Post on December 7, 2017
Briefmarken-Neuausgaben IV. Quartal 2017

Erscheinungstermin 12. Oktober 2017

45. Serie „Deutsche Fernsehlegenden“
„Des Millionenspiel“
Best.-Nr.: 004776
7,– €

46. Serie „Deutschlands schönste Panoramen“
„Badische Weinstraße / Markgräflerland“
Best.-Nr.: 004775
4,50 €

Erscheinungstermin 7. Dezember 2017

54. Serie „Astrophysik“
„GAIA-Satellit“
Best.-Nr.: 004783
4,50 €

55. Serie „Astrophysik“
„Gravitationswellen“
Best.-Nr.: 004782
7,– €

56. Serie „Design aus Deutschland“
„Herbert Lindlinger: Stadtahin Stuttgart“
Best.-Nr.: 004784
14,50 €

57. „100. Geburtstag Heinrich 800“
Board Game by Wittmann
Best.-Nr.: 004785

PDF in Evernote speichern
End of talk

• During this talk about 700,000 stars were measured by Gaia
• About 7 million astrometric measurements,
• 200,000 stellar spectra of 70,000 stars