Gaia: Celestial Inventory from the Solar System to the Milky Way

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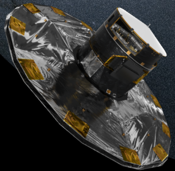


ESA/Gaia/DPAC

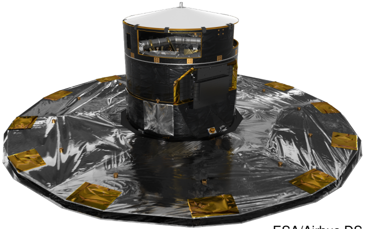
About these lectures

- All slides and other materials on Github
  - https://github.com/agabrown/spitzer-lectures-may2019
- Hyperlinks to papers and web pages are ‘clickable’
- Feel free to re-use the slides but please credit appropriately
  - i.e., use original references to the figures
  - unless otherwise stated figure credits are ‘Anthony G.A. Brown’

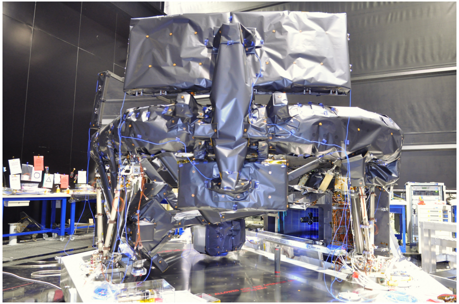
Gaia summary

- Astrometry and spectrophotometry for > 1 billion objects
- Radial velocities for > 100 million objects
- Survey
  - Complete to $G = 20.7$ ($V = 20$–22)
  - Observing programme: autonomous on-board detection and unbiased
  - Quasi-regular time-sampling over 5 years (~ 70 observations)
- Launch December 2013
- 5 years of operations at L2

- Second data release April 25 2018
- Photometric alerts started in 2014
- Alerts on new solar system objects started end 2016



ESA/Airbus DS



Gaia summary

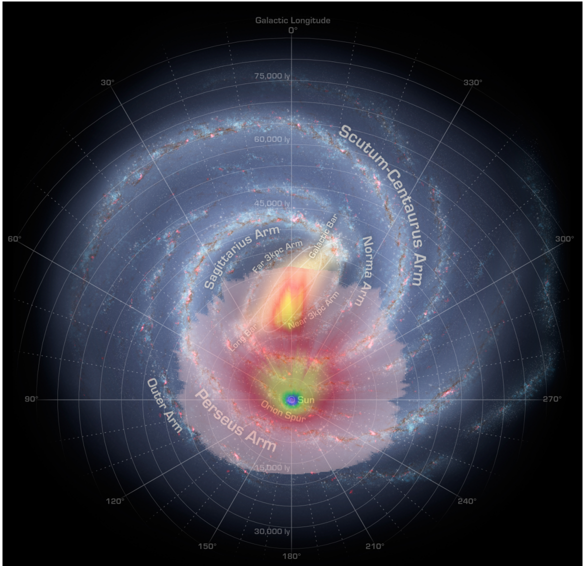
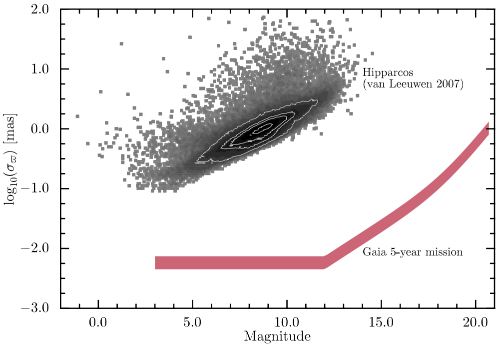
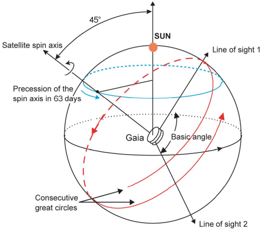
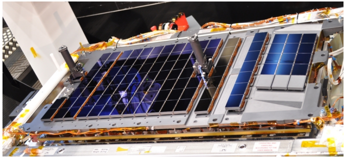


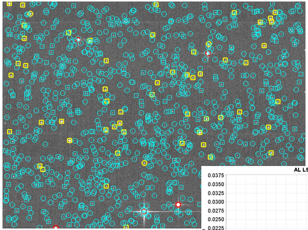
Figure courtesy Xavier Luri, DPAC-CU2 and NASA/JPL-Caltech/R. Hurt

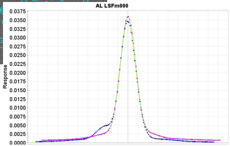


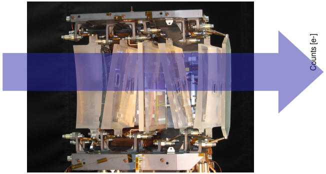
Gaia instruments and measurements

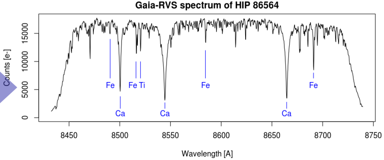


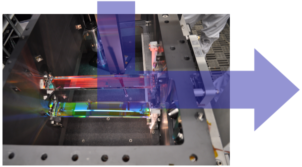


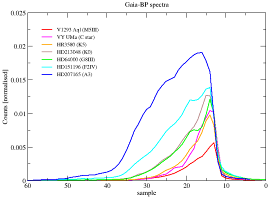


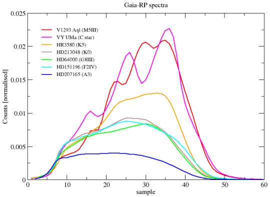












gaia

Gaia DPAC

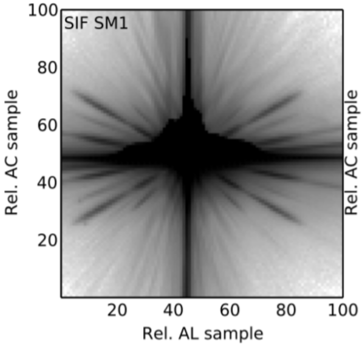
AIRBUS DEFENCE & SPACE

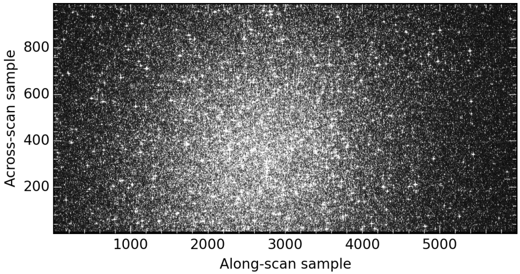
Mission numbers

Gaia status as of 2019-05-01T20:49:25 (TCB)	
Satellite distance from Earth (in km)	1 594 924
No. of days having passed since 25 July 2014	1 742
Operations data (collected since 2014/07/25)	
Volume of science data collected (in GB)	65 657
No. of object transits through the focal plane	125 377 291 682
No. of astrometric CCD measurements	1 235 861 875 147
No. of photometric CCD measurements	250 272 026 278
No. of spectroscopic CCD measurements	24 152 848 743
No. of object transits through the RVS instrument	8 062 009 945

Additional science observations

- Special observation modes to address two shortcomings
  - crowded regions
  - very bright stars ($G < 2$–3)





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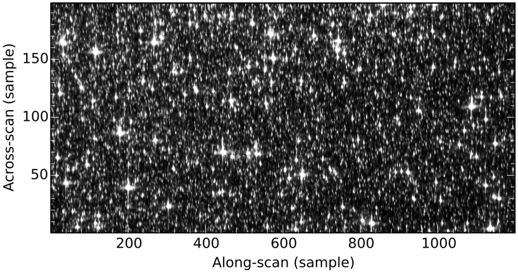
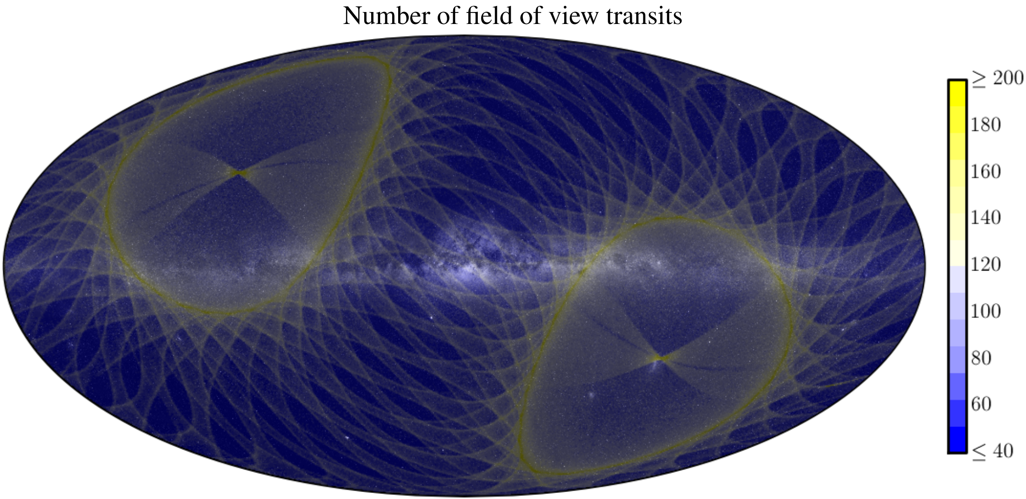


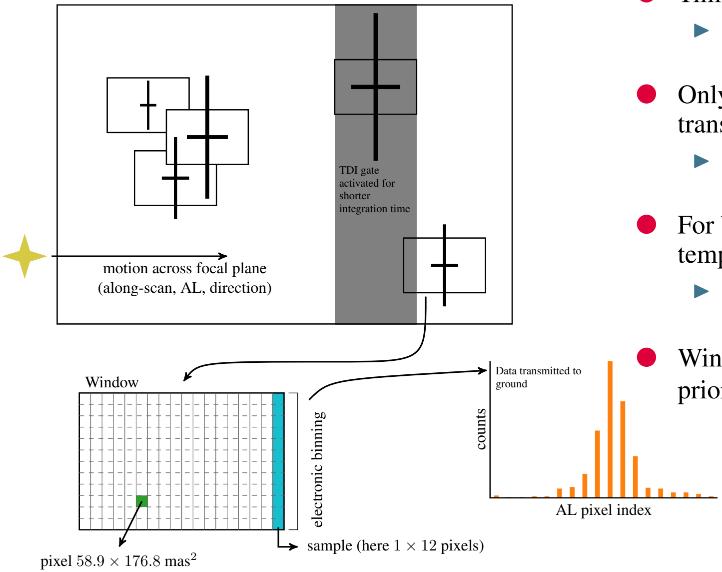
Images: ESA/Gaia/DPAC/SOC Calibration Team

Data collection



Scan law simulations with AGISLab (Holl et al., 2010); image courtesy ESO/S. Brunier

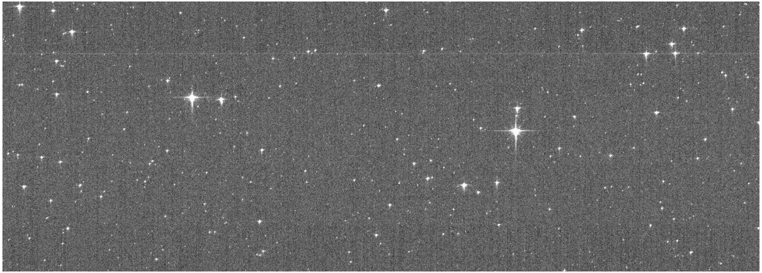
Data collection



- Time-delayed integration
  - photo-electrons shifted along with image every 982.8 μs
- Only pixels in ‘windows’ around sources transmitted to ground
  - mostly 1D windows (binned across-scan); 2D only for bright sources ($G \lesssim$ 8–13)
- For bright sources integration time is temporarily lowered
  - affects other sources observed around the same time
- Window ‘conflicts’ resolved through higher priority for brighter sources

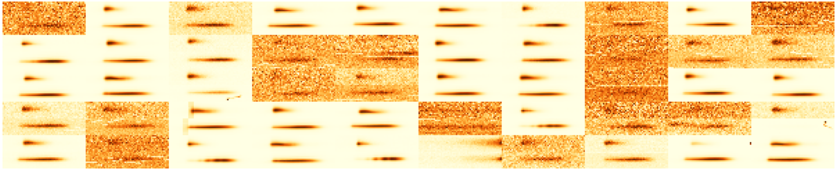
Data collection

Raw astrometric data

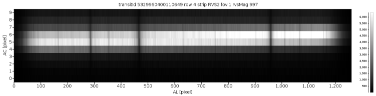


Images: ESA/Gaia/DPAC

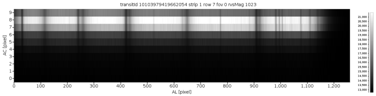
Raw photometric data

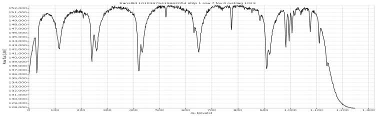


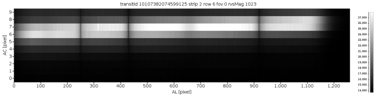
Raw spectroscopic data

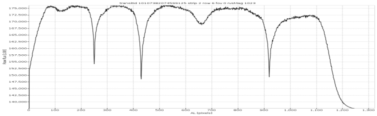


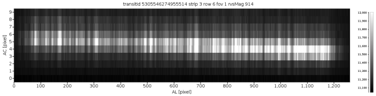
Images: ESA/Gaia/DPAC

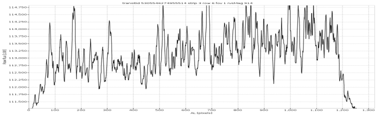








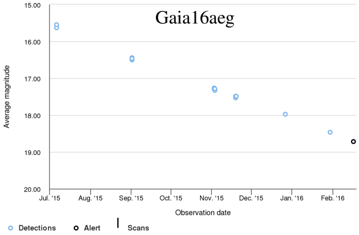


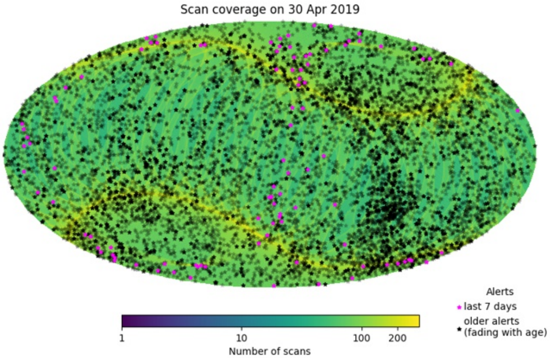


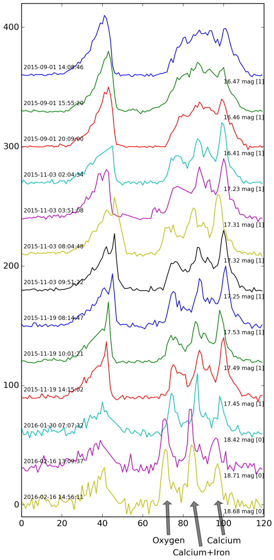
Photometric alerts

ESA/Gaia/DPAC/Gaia Science Alerts Team/Morgan Fraser/Simon Hodgkin/Lukasz Wyrzykowski

http://gsaweb.ast.cam.ac.uk/alerts/home







Solar system alerts

https://gaiafunsso.imcce.fr/index.php

B. Carry (OCA), W. Thuillot (IMCCE)

Where's Gaia?

https://www.eso.org/public/news/eso1908/
http://sci.esa.int/gaia/61327-observing-gaia-from-earth-to-improve-its-star-maps/

Gaia data processing

Find the source parameters

$$\alpha,\ \delta,\ \varpi,\ \mu_{\alpha*},\ \mu_\delta,\ v_\mathrm{rad},\ \text{orbit parameters multiple stars,}$$
$$G,\ \text{colours},\ T_\mathrm{eff},\ [\mathrm{Fe/H}],\ \log g,\ A_0,\ \text{solar system object orbits,}$$
$$\text{light curves},\ \text{variable star classification},\ \ldots$$

and instrument (calibration) parameters

$$\{\text{Collection of parameters describing Gaia}\}$$

that best explain the Gaia observations.

Teamwork for a billion stars

- 15+ years of effort
- 430 scientists and engineers
- 100 institutes
- 24 countries and ESA
- 6 data processing centres
- Funding: national space/funding agencies and ESA

gaia

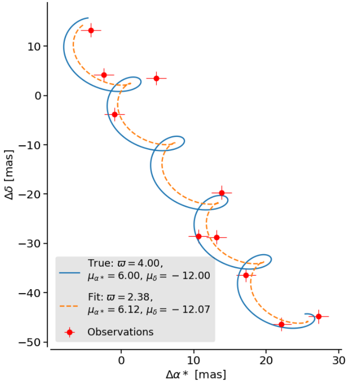
0 1 0 0 0 0 0 0 1 1 0 0 1 0 0 1 1 0 0 1 1 0 1 1 0 0 1 0 1 0

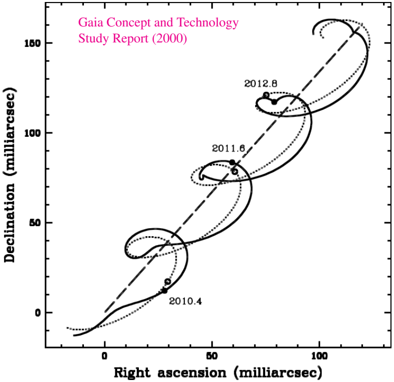
Gaia DPAC
Data Processing & Analysis Consortium

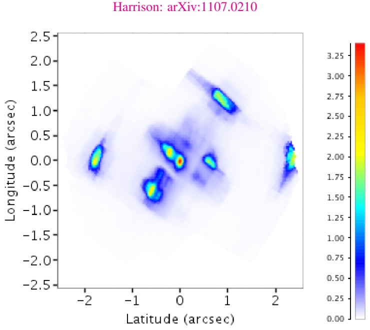
α δ ϖ $\mu_{\alpha*}$ μ_δ G ...

Overview of current and planned Gaia data release contents

Astrometry

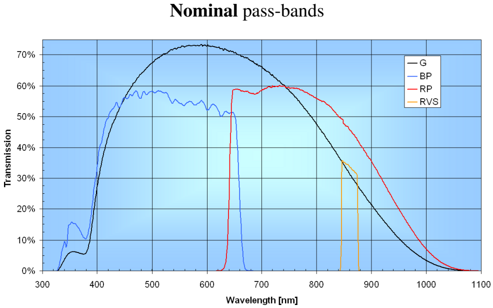


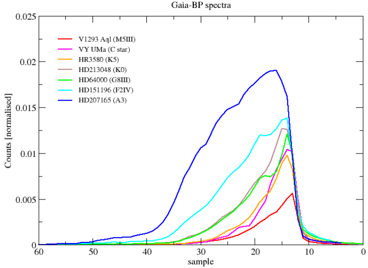




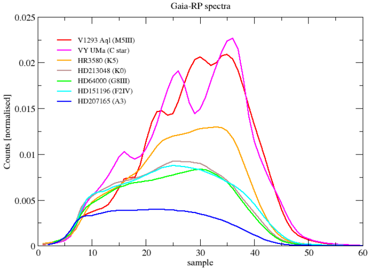
- α, δ, ϖ, $\mu_{\alpha*}$, μ_δ for all sources ($>$ 1 billion)
- Epoch astrometry analysis
  - non-single stars, including exoplanets
  - minor planets in the solar system
  - all epoch astrometry will be released eventually
- Source environment characterization
  - Stack pixels in the windows around each source
  - resolved doubles, improved source astrometry, slight deeper survey

Photometry





Blue Photometer
330–680 nm
3–27 nm/pixel

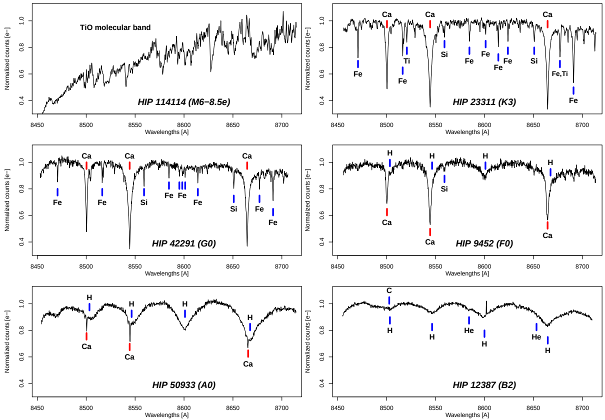


Red Photometer
640–1050 nm
7–15 nm/pixel

- Broad photometry G, $G_{\rm BP}$, $G_{\rm RP}$, $G_{\rm RVS}$
- Low resolution prism spectrophotometry (BP/RP)
- Time series for all sources (Gaia DR4+)
  - including at the CCD level

Images: ESA/Gaia/DPAC/Airbus DS

Spectroscopy

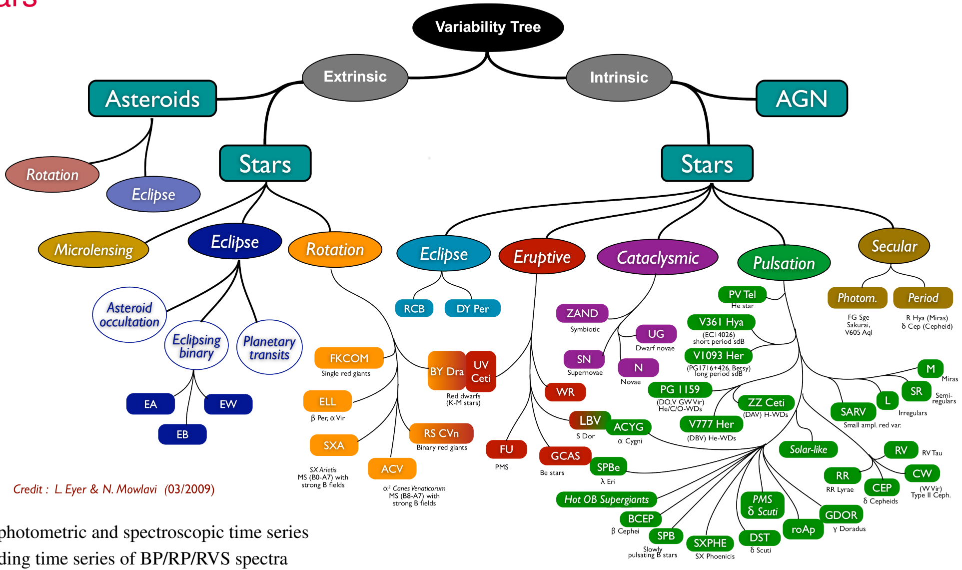


Radial Velocity Spectrometer:
845–872 nm, Ca Triplet region, $R \sim 11\,700$

- Radial velocities for all sources to $G_{\mathrm{RVS}} = 16$ ($G \sim 17$)
- Coarse stellar parameters to $G_{\mathrm{RVS}} \approx 14.5$
- Astrophysical information (extinction, reddening, $v \sin i$, atmospheric parameters) to $G_{\mathrm{RVS}} \approx 12.5$
- Individual abundances (e.g., Fe, Ca, Mg, Ti, Si) to $G_{\mathrm{RVS}} \approx 11$
- Radial velocity time series to $G_{\mathrm{RVS}} \sim 12$–13
  - spectroscopic binaries
  - eclipsing binaries
  - variable star v_{rad} curves

Images: ESA/Gaia/DPAC/Observatoire de Paris-Meudon/Olivier Marchal & David Katz

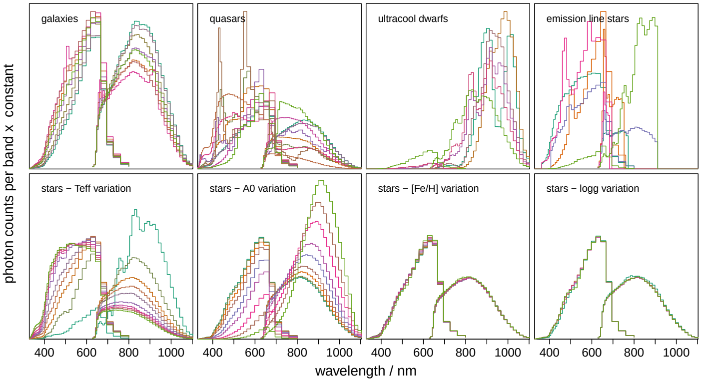
Variable stars



Credit : L. Eyer & N. Mowlavi (03/2009)

- Analysis of photometric and spectroscopic time series
  - including time series of BP/RP/RVS spectra
- Variable source identification, classification, characterization

Astrophysical classification and parametrization

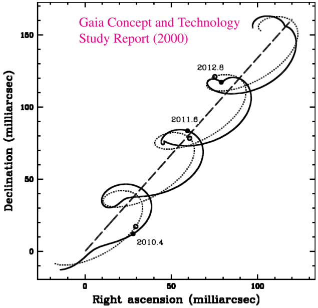


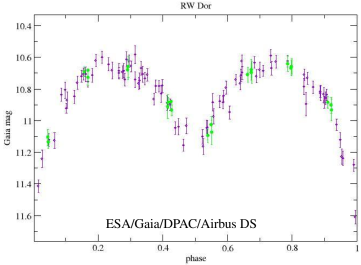
Bailer-Jones, et al., 2013, arXiv:1309.2157

- Analysis of combination astrometry, photometry, spectroscopy
- Discrete source classification (Star, WD, binary, QSO, galaxy)
- Astrophysical parameters (including components of multiple stars)
  - T_{eff}, A_G, $\log g$, $[\mathrm{Fe}/\mathrm{H}]$
  - $[\alpha/\mathrm{Fe}]$, individual abundances, for the brighter stars
  - Luminosity, radius, age, mass estimates
- QSO and unresolved galaxy classifier
- Extinction map
- Outlier analysis

Non-single stars, exoplanets

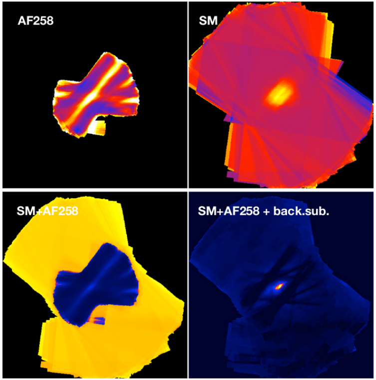
- Astrometric treatment of all sources not conforming to single-star model
  - Use increasingly complex models from perspective acceleration to orbital solutions
- Binaries for large range of separations and ΔG
- Exoplanets
  - detection limit $\sim 1\ M_J$, $P < 10$ yr
  - census of all stellar types over $P = 2$–9 yr
- Spectroscopic binaries
- Resolved multiples
- Astrophysical characterization of eclipsing binaries
- Combined astrometric/ spectroscopic/ eclipsing solutions where possible



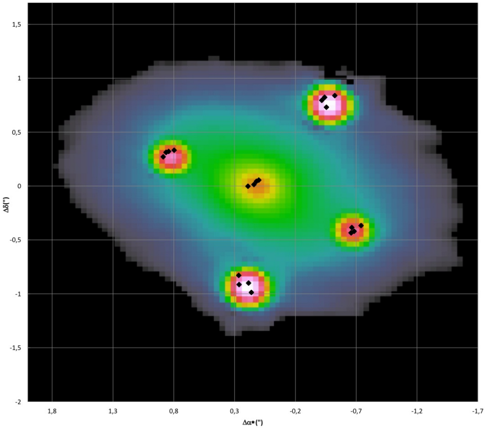


Extended objects

- Stacking of Gaia observation windows to reconstruct images of potentially extended objects
- Galaxy morphology characterization
- QSO environment characterization
- Detection of multiple images of lensed sources



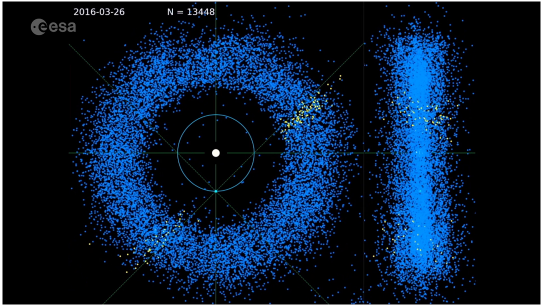
ESA/Gaia/DPAC/
CU4-EO

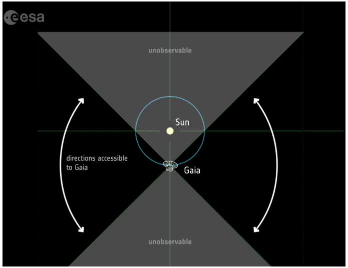


ESA/Gaia/DPAC/Christine Ducourant, Jean-Francois Lecampion (LAB/Observatoire de Bordeaux), Alberto Krone-Martins (SIM/Universidade de Lisboa, LAB/Observatoire de Bordeaux), Laurent Galluccio, Francois Mignard (Observatoire de la Côte d’Azur, Nice)

Solar system objects

- Analysis of epoch astrometry of moving objects in solar system
- Single measurement accuracy of 0.1–1 mas
  - most accurate optical survey ever of minor planets
- Orbits for practically all observed SSOs
  - factor 30 better than existing orbits
  - exotic orbits due to observations at high ecliptic latitude and close to sun
- SSO photometry
  - light curves and taxonomy based on BP/RP spectra
  - rotation and shape properties
  - surface scattering properties
- Powerful combination of accurate dynamics and homogeneous taxonomy





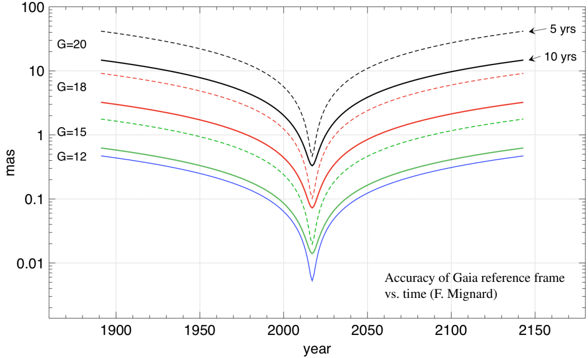
Gaia mission extension

Gaia extension

- Nominal Gaia mission ends mid-2019 after 5 years of measurements
- Hardware in good shape, only limiting factor is micro-propulsion fuel
  - mission can continue to end-2024 (± 0.5 yr)
- Proposal submitted to ESA for 5 year extension
  - approved to end 2020, preliminary approval to end 2022, submit proposal for 2023–2024 in 2020

<u>10 year mission</u>

- Parallaxes, photometry, radial velocities improve by factor 1.4 with respect to DR4
- Proper motions improve by factor of 2.8 with respect to DR4
  - Improvement of more complex motions (e.g., planets) up to factors of 20
- Accurate tangential motions over 22.6$\times$ larger volume

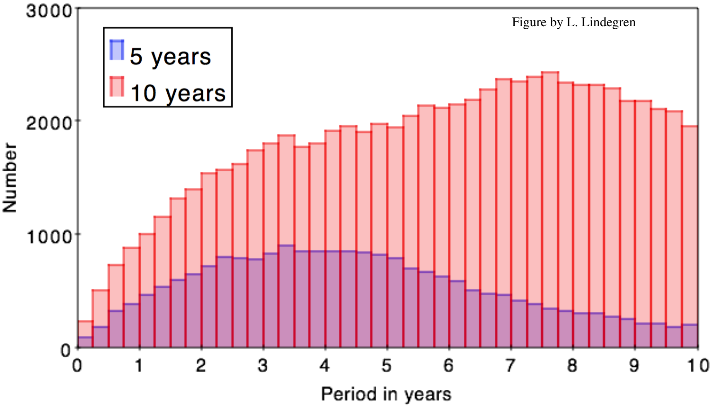


Accuracy of Gaia reference frame vs. time (F. Mignard)

Gaia extension: exoplanets

- Gaia's strength is Neptune-Jupiter mass planets around stars
- Mission extension reveals population of giant planets above several AU distances from the parent star
  - giant planets before migration, systems with giant 'guarding' habitable zone
- Exoplanets research gains enormously from the improved parallaxes helping to describe the host star

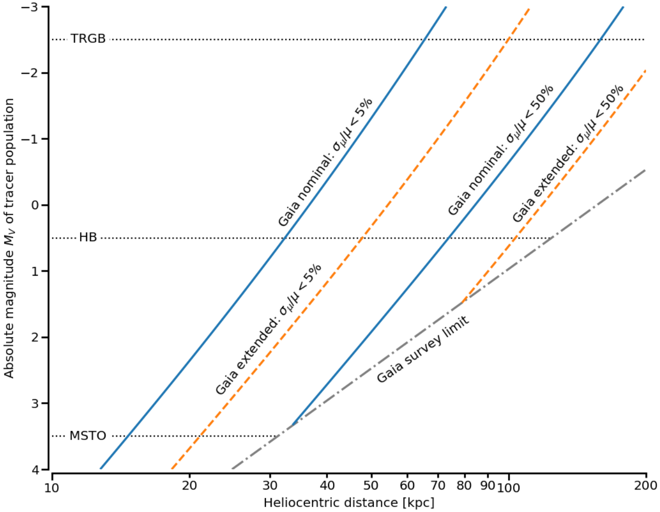
- $\sim$ 20 000 planet discoveries expected out to 500 pc for five year mission
- $\sim$ 70 000 for ten year mission



See Perryman et al. (2014):
https://ui.adsabs.harvard.edu/abs/2014ApJ...797...14P/abstract

Gaia extension: Milky Way halo

- Larger volume reached throughout the halo at given proper motion accuracy
- Uncover more streams
- Probe young and unmixed debris located beyond 20–30 kpc
- Calibration of spectrophotometric distance indicators on nearby samples ⇒ full gain in tangential motion performance



Beyond Gaia

Unique strengths of Gaia

- Global astrometry: absolute parallaxes and proper motions to unprecedented accuracies
- All sky, homogeneous, multi-epoch photometry and spectroscopy.
- Spectroscopy for numbers of objects out of reach of ground based efforts.
- Mapping of the full sky at HST-like angular resolution to 20th magnitude.

None of this is achievable from the ground

- Amplification effect of survey that benefits all areas of astronomy
  - RAVE, WEAVE, 4MOST, MOONS, SDSS-V, GALAH, SkyMapper
  - examples of spectroscopic/photometric instruments/surveys stimulated by the prospect of Gaia

Strategies for choosing future space or ground based surveys

Informed by results from Gaia and other surveys

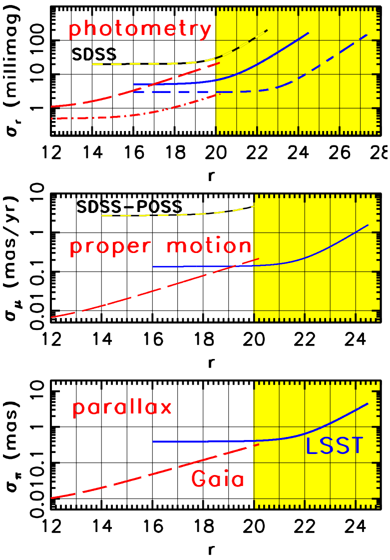
- What are the new questions (surprises) from the Gaia data (combined with other surveys)?
- Which questions were left unanswered in the era of Gaia?
  - e.g., precision dynamics throughout local group
- Which classes of astronomical sources did not (fully) benefit from Gaia?
  - e.g., very low-mass main sequence stars
- Do we need better parallaxes, or proper motions, or both?
- Does spectroscopy offer more information in the medium term?

Survey new wavelength or accuracy domain

- Always turns up interesting new science
- Competitive on longer term
- Technically very challenging

Ground based options (incomplete!)

LSST Science Book Version 2.0 (2009)



<u>Wide field</u>

- LSST: proper motions to 0.5 mas yr^{-1} at $r \sim 23$
  - Absolute astrometry through calibration onto Gaia reference frame

<u>Narrow field</u>

- GRAVITY at VLT: 20–70 μas in K-band
- MICADO at E-ELT: 50 μas for brighter sources over 50 arcsec field of view (0.8–2.4 *mu*m)
- ...

Basic accuracy scaling I. Astrometric performance

Astrometric performance depends on the image location precision, $\sigma_{\rm loc}$:

$$\boxed{\sigma_{\rm loc} \geq \frac{\sqrt{3}}{2\pi}\frac{\lambda_{\rm c}}{B\sqrt{N_{\rm photons}}}}$$

$$N_{\rm photons} = A \times t_{\rm obs} \times \int T(\lambda)Q(\lambda)S(\lambda)\,d\lambda$$
$$\approx A \times t_{\rm obs} \times F(\lambda_{\rm c}) \times {\rm EBW}$$

$\lambda_{\rm c}$	(Effective) central wavelength of observational band
B	Mirror size or baseline of interferometric configuration
A	Aperture area
$t_{\rm obs}$	Total observing time per source
$F(\lambda_{\rm c})$	Received photon flux at wavelength $\lambda_{\rm c}$ ($\rm m^{-2}\ nm^{-1}\ s^{-1}$)
EBW	Equivalent bandwidth $= \int T(\lambda)Q(\lambda)\,d\lambda$
$S(\lambda)$	Received source flux in photons $\rm m^{-2}\ nm^{-1}\ s^{-1}$
$T(\lambda)$	Telescope transmissivity
$Q(\lambda)$	Detector quantum efficiency

EBW approximation is valid only in case of approximately flat spectrum sources, such as solar-type stars in the optical.

Material on this slide based on Lindegren (2005)

Basic accuracy scaling II. Proper motions from combined surveys

Proper motion precision depends image location precision of individual surveys and time baseline:

$$\sigma_{\rm pm} = \frac{\left(\sigma^2_{\rm Gaia} + \sigma^2_{\rm future}\right)^{1/2}}{T} = \frac{\left(\sigma^2_{\rm Gaia} + \eta^2\sigma^2_{\rm Gaia}\right)^{1/2}}{T} \quad \longrightarrow \quad \frac{\sigma_{\rm pm,Gaia}}{\sigma_{\rm pm}} \approx 1.4 \times \frac{T}{(1+\eta^2)^{1/2}}$$

T	time difference between mean epochs of both surveys
$\sigma_{\rm Gaia}$, $\sigma_{\rm future}$	precision on celestial positions for Gaia and some future survey
$\sigma_{\rm pm,Gaia}$	Gaia proper motion precision (roughly $0.7 \times \sigma_{\rm Gaia}$)
$\sigma_{\rm pm}$	proper motion precision from combined surveys
η	ratio of position precisions $\sigma_{\rm future}/\sigma_{\rm Gaia}$

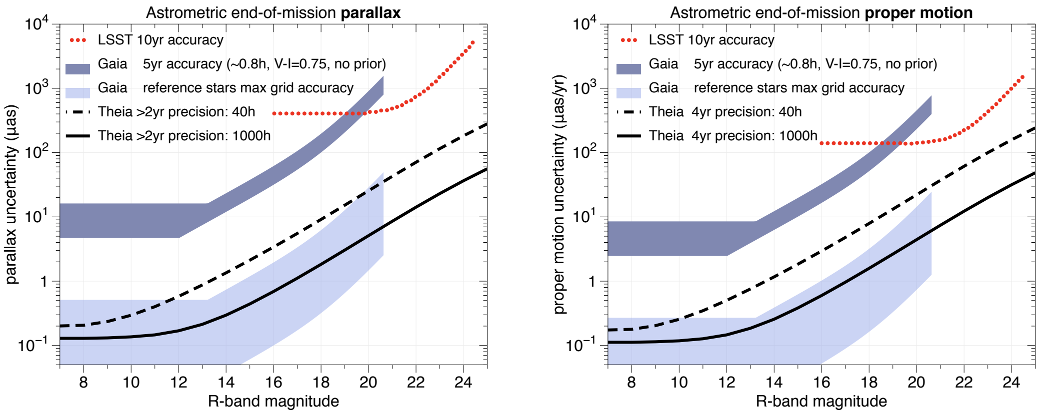
- Considerations on σ from previous slide apply
- $\sigma_{\rm future}$ may also contain component due to Gaia future reference frame uncertainty (e.g. WFIRST, LSST, both calibrated to Gaia)

Proposed or under study space astrometry missions

Missions below go beyond Gaia capabilities for Milky Way studies

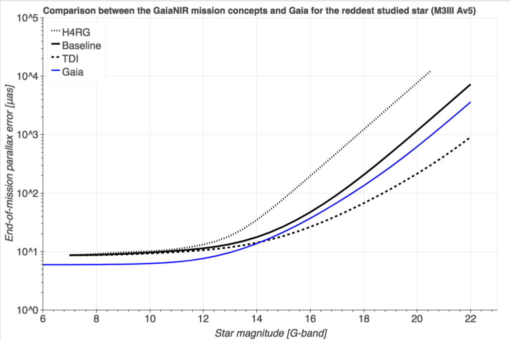
- Small-JASMINE (NAOJ, under review for selection)
  - $H_{\rm w}$ band (1.1–1.7 μm)
  - 0.7 degree radius field around Galactic centre
  - 20 μas parallax, $\lesssim$ 50 μas yr^{-1} proper motions at $H_{\rm w} < 12.5$
- Theia (ESA M5 proposal, not selected)
  - 350–950 nm
  - 0.5 deg^2 field of view, targeted differential astrometry
  - $\sim$ 0.2 mas yr^{-1} proper motions at $r \sim 23$
- GaiaNIR (ESA conceptual design study completed, not currently in ESA programme)
  - 400–1800 nm
  - at $G = 21 \sim 0.3$ to 30 mas positions, strongly dependent on mission option and spectral type
  - Gaia-TDI concept requires development TDI-capable IR detectors
  - significant gains in proper motion accuracy when combined with Gaia (factors 4 to 14)
  - many reddened sources will be observed by GaiaNIR but not Gaia
- WFIRST `https://arxiv.org/abs/1712.05420`
  - 0.5–2 μm
  - Relative proper motions at high latitude to 25μas yr^{-1}, relative positional astrometry to 1–10 μas
  - Absolute astrometry to 0.1 mas (calibrated to Gaia reference frame)

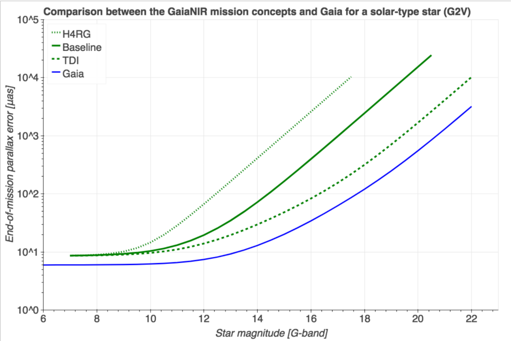
Theia performance predictions



Boehm et al. (2017): arXiv:1707.01348

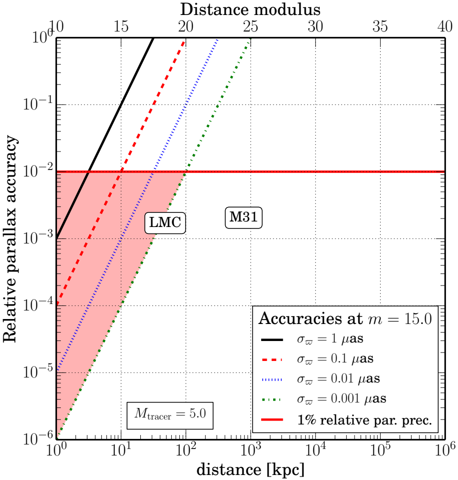
GaiaNIR performance predictions

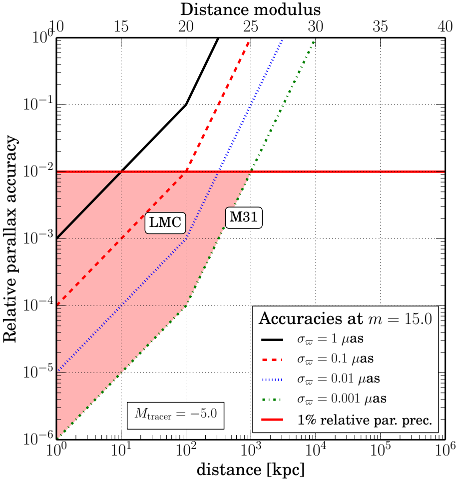




GaiaNIR CDF study report: `http://sci.esa.int/jump.cfm?oid=60028`

Parallax accuracies required for direct distance measurements local group

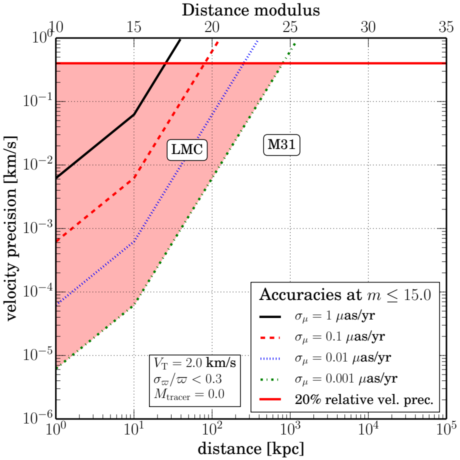




From White paper for ESA L2/L3 call:

http://www.rssd.esa.int/doc_fetch.php?id=3210644

Proper motion accuracies required for precise tangential motions local group



From White paper for ESA L2/L3 call:
http://www.rssd.esa.int/doc_fetch.php?id=3210644

Some of the challenges of sub-μas astrometry

<u>Constraints</u>

- Assume astrometric precision scales as:

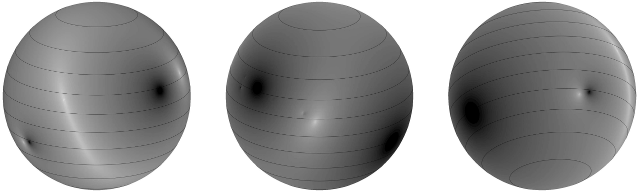
$$\sigma \propto \frac{\lambda}{B\sqrt{N}}$$

- Scaling up baseline B is the only realistic improvement in the optical
  - interferometric mission with collecting areas of a few m^2 and baselines of 100–1000 meter
- How to do global astrometry with such a configuration?

<u>Engineering</u>

- Precision formation flying
- Thermo-mechanical stability demands, attitude control, knowledge of spacecraft position/velocity
- Photon collection robust to radiation damage effects

Some of the challenges of sub-μas astrometry



Magnitude of light deflection due to solar system planets at some fixed moment in time as distributed on the celestial sphere shown from three sides

Klioner 2012, MmSAI, 83, 994

Conceptual and data processing

- Relativistic modelling of astrometric measurements in nano-arcsec regime?
  - metric and light propagation laws in fields of N arbitrary bodies with full multipole structure
  - improved knowledge solar system (e.g., asteroid masses)
  - extreme orbit determination requirements for spacecraft
- System calibration extremely challenging
  - should be better by order of magnitude than astrometric precision aimed for
- Research into proper modelling of time dependence of source coordinates
  - investigate sources of astrometric jitter (star spots, μ-lensing, etc)
- Sufficient compact (< 1 AU) bright sources for parallax method at cosmological distances?

Entry points to Gaia literature

Mission, spacecraft, payload, data processing and validation

Initial Gaia proposal (1993)
http://www.astro.lu.se/~lennart/Astrometry/gaia_proposal.PDF

Gaia Concept and Technology Study Report (1998–2000)
http://www.rssd.esa.int/doc_fetch.php?id=359232

Gaia presentation Science case and mission description in 2001
https://doi.org/10.1051/0004-6361:20010085

Gaia DR1 A&A special issue Data processing and validation
https://www.aanda.org/component/toc/?task=topic&id=641

Gaia DR2 A&A special issue Data processing and validation
https://www.aanda.org/component/toc/?task=topic&id=922

Mission, instruments, and data processing overview
https://doi.org/10.1051/0004-6361/201629272

RVS detailed description https://doi.org/10.1051/0004-6361/201832763

On-board detection capabilities https://doi.org/10.1051/0004-6361/201424018

In-orbit CCD performance https://doi.org/10.1051/0004-6361/201628990

Documentation http://gea.esac.esa.int/archive/documentation/index.html

Entry points to Gaia literature

Description of Gaia data products, mostly pre-launch

Gaia broad-band photometry `https://doi.org/10.1051/0004-6361/201015441`

Astrophysical parameters `https://doi.org/10.1051/0004-6361/201322344`

Astrophysics from RVS `https://doi.org/10.1051/0004-6361/201425030`

Double and multiple stars `http://dx.doi.org/10.1063/1.3597594`

Variable stars `https://doi.org/10.1051/eas/1567012`

Solar system `https://doi.org/10.1016/j.pss.2012.03.007` and
`https://doi.org/10.1016/j.pss.2015.11.009`

Galaxy morphology with Gaia `https://doi.org/10.1051/0004-6361/201219697`

Source environment analysis `https://doi.org/10.1007/s10686-011-9240-7`

Transient astronomy `https://doi.org/10.1098/rsta.2012.0239`

Simulated Gaia data `https://doi.org/10.1051/0004-6361/201118646` and
`https://doi.org/10.1051/0004-6361/201423636`

Entry points to Gaia literature

Astrometry with Gaia

Astrometric Global Iterative Solution https://www.aanda.org/articles/aa/abs/2012/02/aa17905-11/aa17905-11.html

Relativistic astrometric model for Gaia observations https://doi.org/10.1086/367593

Tycho-Gaia Astrometric Solution https://doi.org/10.1051/0004-6361/201425310

Beyond Gaia

White paper on sub-μas astrometry options http://www.rssd.esa.int/doc_fetch.php?id=3210644

Study report on GaiaNIR http://sci.esa.int/jump.cfm?oid=60028