Exoplanets in Gaia Data Release 4

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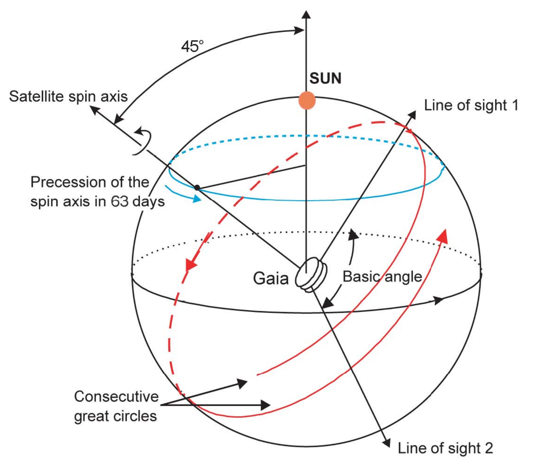
Introduction

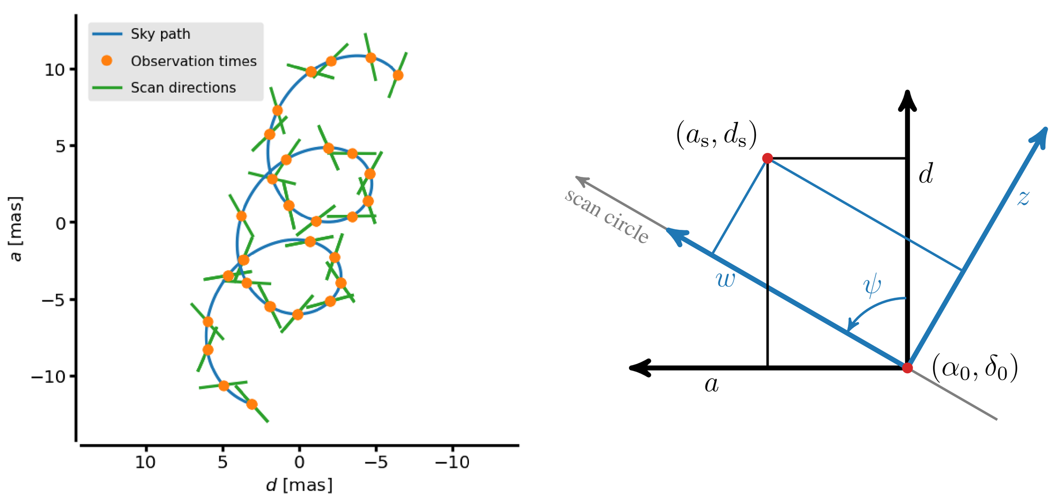
The astrometric detection of exoplanets has long been heralded as a very promising technique. Gaia now provides the per-epoch position measurement precision needed for a comprehensive survey, and its potential for the discovery and characterization of exoplanets through astrometry was demonstrated with the release of Gaia DR3 (Holl et al. 2023b).
Gaia DR4 will contain a catalogue of (candidate) exoplanets and *per-epoch astrometry for all Gaia sources*, thus enabling the community to conduct further searches for exoplanets and other companions to Gaia stars.

Survey principle



The sky survey strategy relies on revolving scanning which determines the observation cadence of sources. The position information is precise only along the great circles traced out by Gaia's two telescopes.

Epoch astrometry format



Left: Gaia's high precision position information is along one dimension, coinciding with great circles scanned by its telescopes (green lines). **Right:** Epoch astrometry is defined in terms of local plane coordinates (a, d) with respect to reference position (α_0, δ_0). Epoch astrometry in Gaia DR4 is published as local scan coordinates (w, z) (along scan, across scan), uniquely defined by the position angle ψ of the scan direction.

$$
\begin{aligned}
w &= \quad a\sin\psi + d\cos\psi \\
z &= -a\cos\psi + d\sin\psi
\end{aligned}
$$

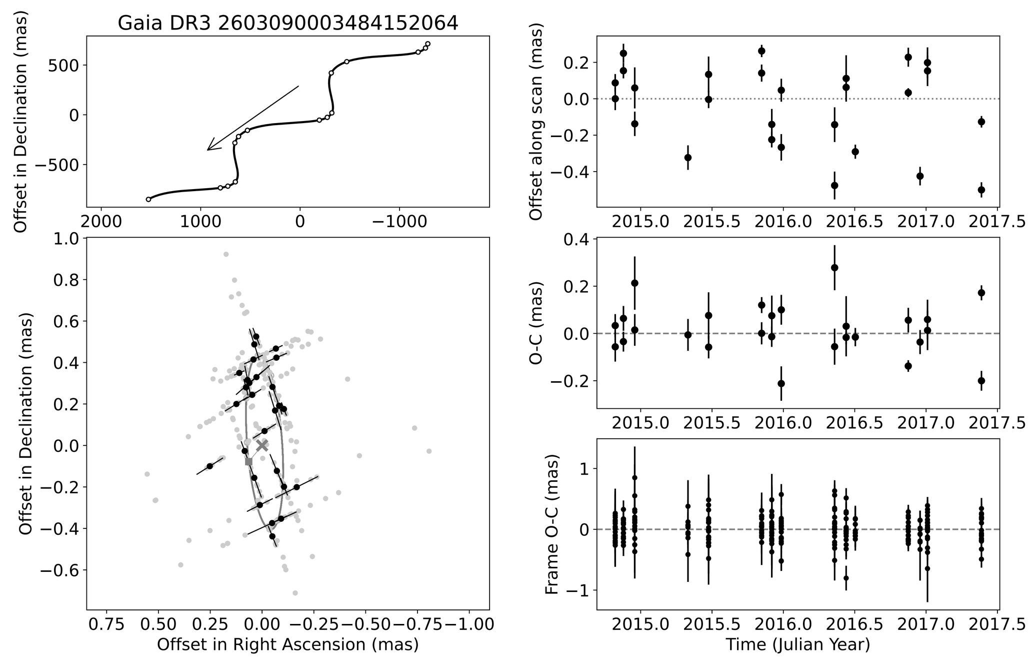
Astrometric model star + single exoplanet (z can be ignored):

$$
w = (\Delta\alpha * +\mu_{\alpha *}t)\sin\psi + (\Delta\delta + \mu_\delta t)\cos\psi + f_w\varpi + (BX + GY)\sin\psi + (AX + FY)\cos\psi\,,
$$

- A, B, F, G: Thiele-Innes coefficients
- X, Y: Keplerian orbit model
- f_w: along scan parallax factor (provided along with observation times)

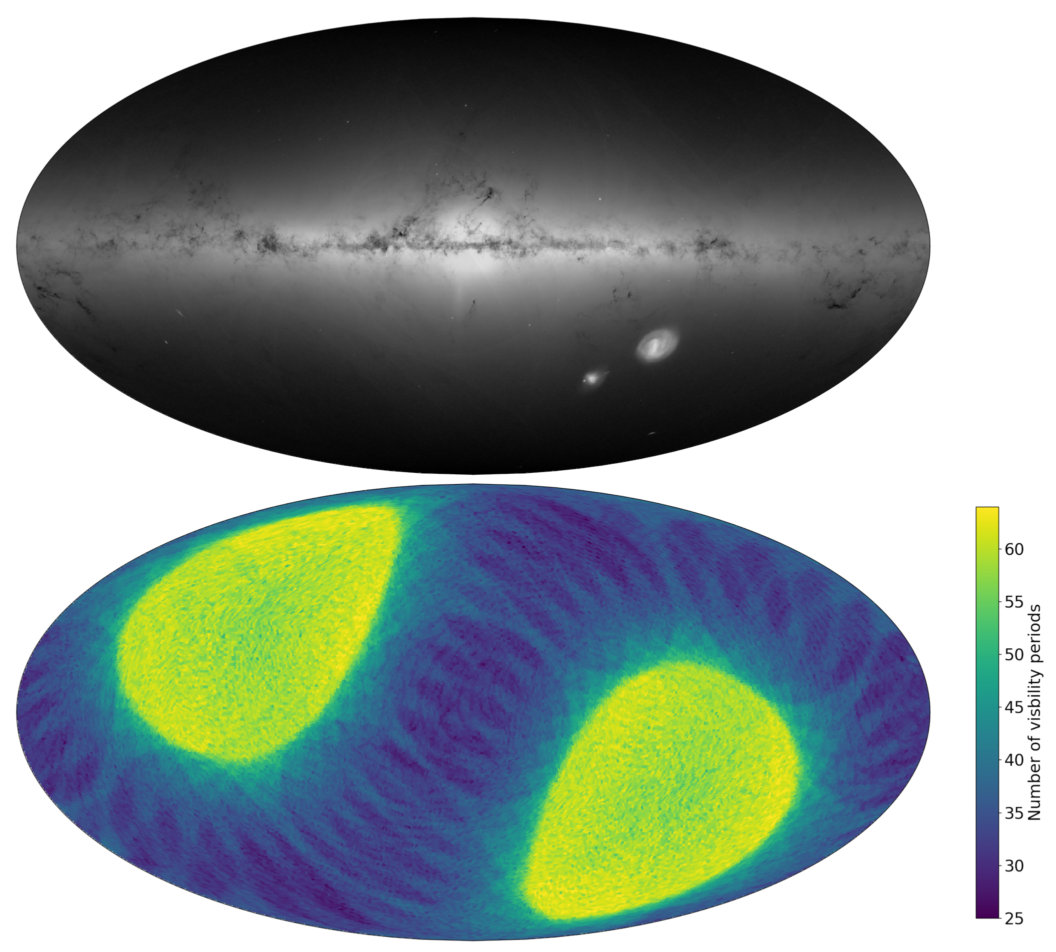
For details see Lindegren & Bastian (2022). Exoplanet detection capabilities thus strongly depend on details of observation cadence and scan angle distribution (see box on scan law).

Example Gaia DR3 result



Astrometric orbit of Gl 876 ($G = 8.88$ mag, $P = 61.36 \pm 0.22$ day, $e = 0.16 \pm 0.15$, $\varpi = 213.79 \pm 0.07$ mas). **Top left:** the solid curve shows the parallactic and proper motion. Open circles indicate the observation times. **Bottom left** the sky-projected orbit model about the barycentre (marked with 'x') is shown in grey and astrometric measurements and normal-points after subtraction of parallax and proper motion are shown in grey and black, respectively. Only along-scan astrometry was used, therefore the offsets shown are projected along Gaia's instantaneous scan angle, whose orientation is indicated by the error-bars. **Top right:** the normal points after subtraction of the parallax and proper motion as a function of time. **Middle and bottom right:** the post-fit residual normal-points and individual CCD-transit data, respectively. Normal-points are computed at every field-of-view transit of the star from the ~9 individual CCD transits and are only used for visualisation. The data processing used individual CCD-transit data. Figure and caption adapted from Holl et al. (2023b).

Gaia DR4 scan law statistics

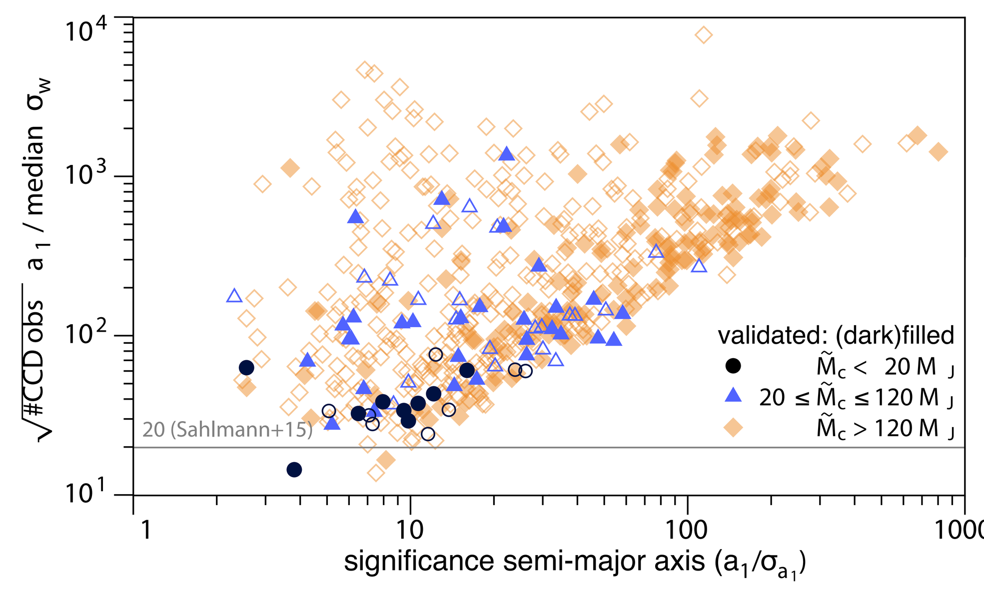


Top: Gaia DR3 source density distribution (for orientation, galactic coordinates). **Bottom:** number of visibility periods (number of groups of observation times separated by at least 4 days), i.e. the number of truly independent astrometric measurements. A higher number of visibility periods gives a better chance at finding multiple planets. For more insights into the scanning law see Holl et al. (2023a).

Gaia discovery space, expected yield

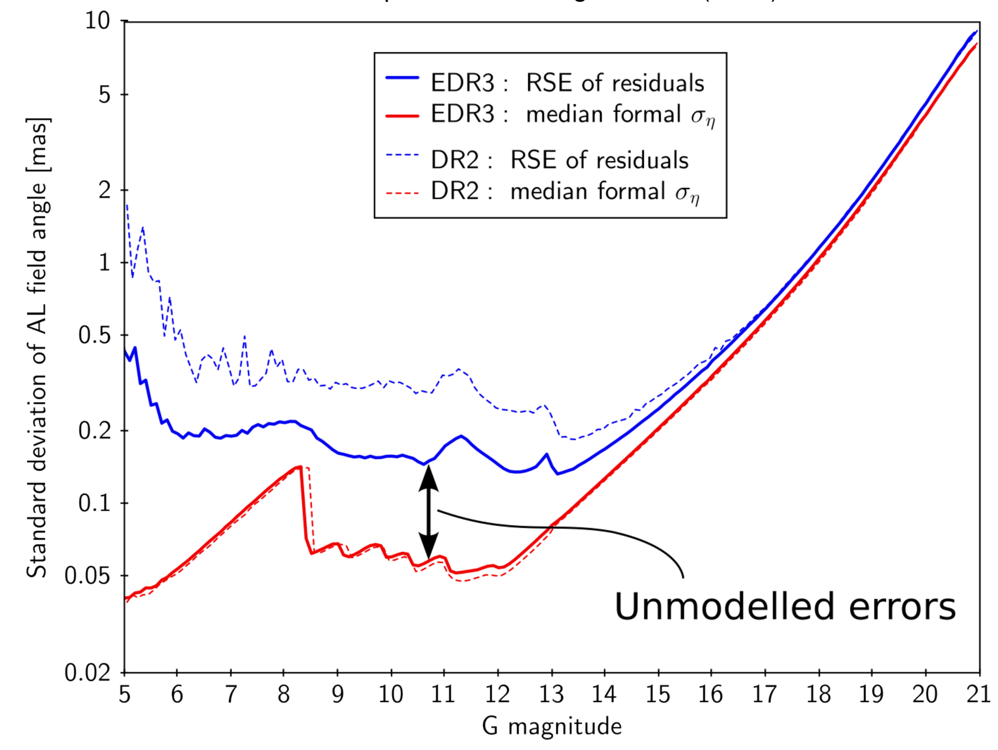
- Exoplanet survey of $\sim 10^6$–10^7 stars, unbiased across spectral type, age, chemical composition of the primary.
- Thousands of giant planet ($< 15\,M_{\rm Jup}$) discoveries predicted around A to M type stars (Casertano et al. 2008; Sozzetti et al. 2014; Perryman et al. 2014; Sahlmann et al. 2015; Ranalli et al. 2018; Holl et al. 2022).
- Number could triple for the 10 year observation time span of Gaia DR5.
- Actual performance depends on per-epoch astrometric uncertainties achieved in practice. The plot below shows the Gaia DR3 performance in terms of the significance of the semi-major axis with respect to the median along-scan astrometric uncertainty. The plot corresponds to the OrbitalTargetedSearch[Validated] subset of the Gaia DR3 non-single star astrometric solutions (`nss_two_body_orbit` table).

Credits: adapted from Holl et al. (2023b)



- Existing Gaia exoplanet yield predictions assume per-epoch astrometric uncertainty of $20\,\mu$as at $G \lesssim 13$.
- The figure below shows the formal per CCD astrometric uncertainties are at the 50–$60\,\mu$as level at $G \lesssim 13$ for Gaia DR3 (red line; enough to achieve 15–$20\,\mu$as when averaged over 9 CCDs).
- Actual Gaia DR3 uncertainties are limited by calibration errors to ~ 0.15–0.2 mas (blue line).
- Gaia DR4 formal uncertainties are similar while the actual uncertainties are at the 0.08–0.15 mas level (30–$50\,\mu$as averaged over 9 CCDs).

Credits: adapted from Lindegren et al. (2021)



Preparing yourself

Details of local scan coordinates definition, rigorous astrometric modelling equations.

Gaia Observation Forecast Tool (GOST): simulate Gaia observation times, scan angles, and parallax factors, according to realistic scanning law.

Real epoch astrometry from preliminary Gaia DR4 astrometric solution plus example usage (for Gaia BH3).

References

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