Reproducing the Solar System Acceleration Detection from Gaia Early Data Release 3 (A & A)

A Summary
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Degree
MPhil Data Intensive Science

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Word Count:
910

GitHub:
https://github.com/MatteoMancini01/Gaia_EDR3

Easter Term 2025

1 Motivation & Scientific Justification

The acceleration of the solar system barycentre relative to distant extragalactic sources provides a unique and direct probe of Galactic dynamics. This subtle acceleration induces a systematic dipole pattern in the proper motions of distant objects, known as the secular aberration drift. Measuring this effect not only tests predictions of Galactic mass distribution but also serves as a stringent validation of global astrometric solutions (Klioner et al. (2021)).

In 2013, the European Space Agency's (ESA) (see Prusti et al. (2016)), launched a space telescope under the Gaia mission (ended 27th of March 2025), with the main objective of scanning the sky to reproduce the most precise 3D map of the Milky Way. Gaia's ability to measure positions and proper motions of over a billion sources enables a new regime of precision astrometry. Quasi-stellar objects (QSOs), or quasars, are ideal reference objects because of their extragalactic distances and negligible intrinsic proper motions. Using these extra galactic sources we ensure that any large-scale proper motion signal is not contaminated by local stellar kinematics, allowing a clean measurement of the solar acceleration vector. The results of our analysis can be beneficial for many reasons, of which: it provides an independent cross-check of Galactic potential models, informs the long-term stability and accuracy of celestial reference frames, and demonstrates Gaia's capacity to detect global kinematic signatures at the microarcsecond level. Additionally, we want to test the reproducibility of the experiments and analysis in Klioner et al. (2021).

2 Model

To conduct our analysis, we utilised a vector spherical harmonics (VSH) decomposition to model the proper motion field of quasars and extract systematic patterns, including the first-order spheroidal components (Klioner et al., 2021; Mignard and Klioner, 2012). Our primary objective was to infer the VSH coefficients, particularly the spheroidal coefficients corresponding to the dipole term, which are related to the solar acceleration vector (Klioner et al. (2021)).

As shown in Figure 1, the statistical weights of quasars are not uniformly distributed across the sky. As a consequence of this non-uniform pattern, a standard least-squares fit would be inappropriate. To reduce potential biases, Klioner et al. (2021) used a weighted least-squares approach combined with 550,000 bootstrap resampling iterations to estimate uncertainties. Additionally, Klioner et al. (2021) performed outlier detection by rejecting sources with residuals exceeding the median by a clipping threshold $\kappa = 3$. For consistency, we adopted the same outlier rejection procedure and tested our model using different clipping values to assess the robustness of our results and to evaluate potential biases associated with specific sources.

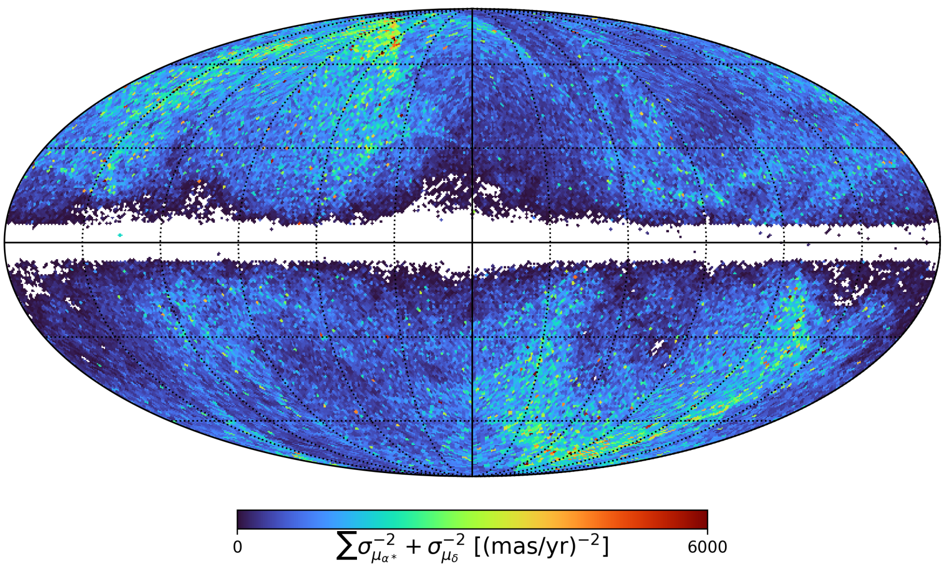

Figure 1: Sky distribution of Gaia-CRF3 QSO-like sources in Galactic coordinates (Mollweide projection), shown as source density per deg^2 using HEALPix binning ($N_{\rm side} = 64$). Regions near the Galactic plane are masked due to extinction and stellar contamination.

However for our main inference experiment we did not follow their footsteps, instead we adopted a Bayesian approach using a Hamiltonian Monte Carlo (HMC) sampling algorithm to both estimate the VSH coefficients and their uncertainties. To sample from the posterior distribution, we needed to specify a Gaussian likelihood function, making the most of the proportionality to the weighted least-squares formulation used by Klioner et al. (2021). For the prior, we chose a standard normal distribution, which is weakly informative and ensures numerical stability.

3 Results & Findings

For our main analysis, after performing the outlier detection algorithm, Klioner et al. (2021), we rejected 3785 sources (this agrees with the ~ 3800 rejected in Klioner et al. (2021)) and then sampled from this filtered dataset. The sampling procedure includes HMC algorithm, with a total of 8 chains, 2000 warm-ups (burn-in period, this is ultimately removed from our result) and 5000 samples per chain. We tested our samples for convergence without finding any anomalies (i.e. divergences). We avoided any potential autocorrelation issues within our posterior samples by estimating the integrated autocorrelation time (IAT), and thinned each sample according to the estimated IAT. Main results are shown in Table 1, comparing these to Table 2, Section 7 in Klioner et al., 2021, one can see that the results in question are practically identical to the uncertainty, demonstrating model robustness and reproducibility of our Bayesian approach.

Table 1: Final estimate of the Solar System acceleration vector. All the uncertainties are with in $\pm 1\sigma$, these are obtained from HMC sampling.

Quantity	**Value**	**Uncertainty**
Equatorial components		
g_x [µas yr^{-1}]	-0.08	0.45
g_y [µas yr^{-1}]	-4.30	0.37
g_z [µas yr^{-1}]	-2.65	0.23
α [deg]	268.97	6.05
δ [deg]	-31.62	3.11
Correlations		
ρ_{g_x,g_y}	-0.092	
ρ_{g_x,g_z}	$+0.020$	
ρ_{g_y,g_z}	$+0.001$	
$\rho_{\alpha,\delta}$	$+0.042$	
Galactic components		
g_X [µas yr^{-1}]	$+5.04$	0.34
g_Y [µas yr^{-1}]	-0.10	0.34
g_Z [µas yr^{-1}]	-0.29	0.40
l [deg]	358.82	3.87
b [deg]	-3.28	4.61
Correlations		
ρ_{g_X,g_Y}	$+0.307$	
ρ_{g_X,g_Z}	$+0.081$	
ρ_{g_Y,g_Z}	-0.466	
$\rho_{l,b}$	-0.008	
$\lvert\mathbf{g}\rvert$ [µas yr^{-1}]	5.05	0.34

Figure 2, represents the 2D joint posterior distribution of the celestial coordinates right ascension (RA) and declination (Dec) in degrees. The red cross represent the location of the galactic centre, which lies well within the high-density region of the inferred posterior, indicating that our recovered acceleration direction is statistically consistent with the expected direction towards the galactic centre. This result supports the detection of the secular aberration drift due to the solar system's acceleration within the Milky Way.

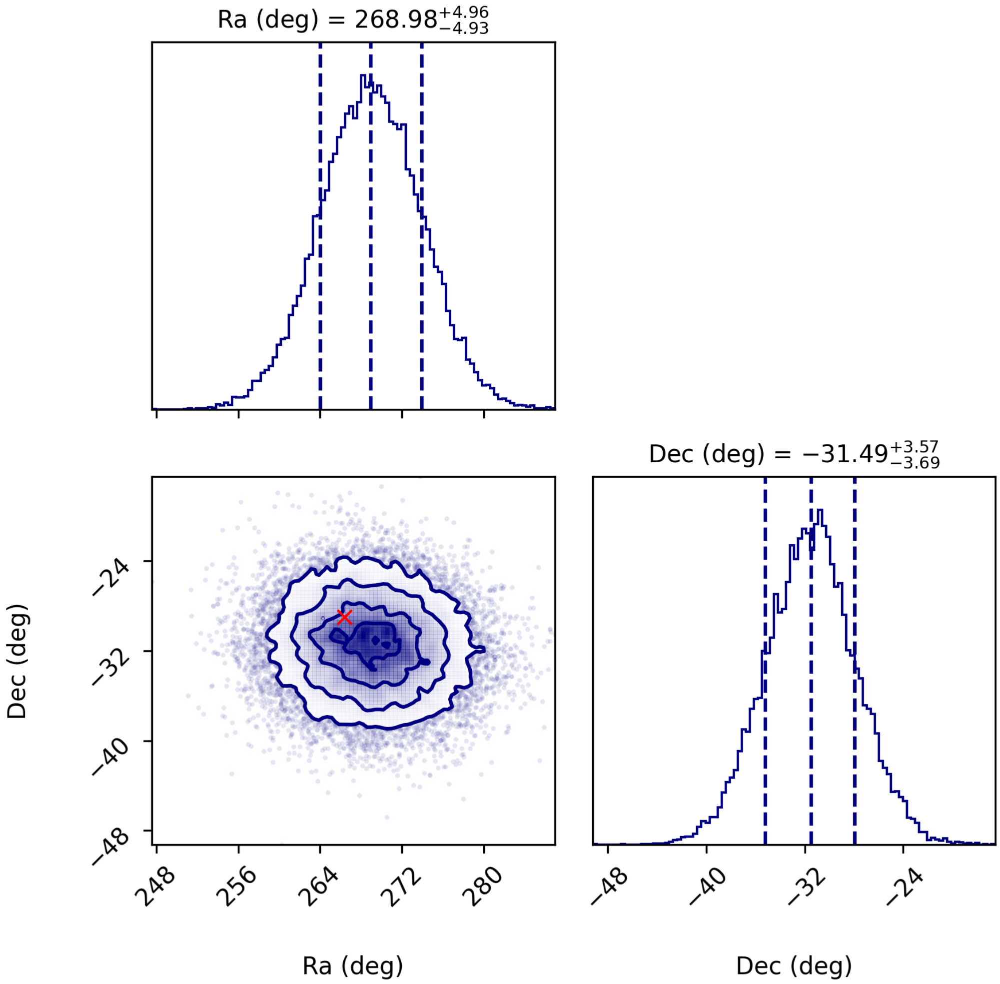

Figure 2: 2D joint distribution of the RA and Dec samples. The red cross indicates the location of the Galactic centre, located at $\alpha \approx 266.42°$, $\delta \approx -29.01$ (Reid and Brunthaler, 2004).

4 Impact & Future Work

This work provides an independent confirmation of the solar system's acceleration measurement using Gaia EDR3. It reinforces the reliability of the Gaia astrometric solution and the vector spherical harmonics (VSH) framework. We adopted a Bayesian approach with Hamiltonian Monte Carlo sampling. This not only validates previous results but also introduces a method that allows for a better handling of parameter uncertainties and correlations.

Our findings increase confidence in Gaia's ability to detect subtle global kinematic signatures, which establishes the inertial celestial reference frame. These results have wider implications for Galactic dynamics. They include constraints on the Milky Way's mass distribution and the local gravitational potential.

The upcoming Gaia data releases will have extended time baselines, allowing potential improvement in proper motion precision and allow for more accurate measurements of the solar acceleration vector. If we adopt more advanced models for Galactic systematics, as well as possible variations from large-scale structure, we could improve our understanding of subtle kinematic effects. Additionally, we could look into different statistical techniques or machine learning methods to improve computational efficiency.

In conclusion, ongoing advancements in astrometry can provide insights into the Galaxy's structure and evolution.

References

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