217. Zero-point of the Gaia parallaxes

GAIA HAS provided a breakthrough in positional astronomy by measuring the parallaxes (and related properties) of nearly 2 billion stars, galaxies, and quasars. The inverse of the parallax in arcsec gives the distance to the source in parsec. For nearby stars with large parallaxes, this simple prescription serves us well.

For more distant sources, parallax errors complicate things considerably. Even for a normal error distribution – which, incidentally, leads to the appearance of (non-physical) negative parallaxes – the distribution of the (reciprocal) distance errors is non-Gaussian, and associated distance estimates are inevitably biased. Bailer-Jones (2015) provides a didactic introduction to this problem, with later papers in the same series going into greater detail (Astraatmadja & Bailer-Jones, 2016a; 2016b; Bailer-Jones et al., 2018; 2021; 2023).

Any *systematic* parallax errors add further complications. Even small systematics affect estimates of the mean properties of distant populations. Examples include determining the cosmological distance scale using Cepheids (e.g. Riess et al., 2021) or the tip of the red giant branch (e.g. Li et al., 2023), or understanding the dynamics of the Large Magellanic Cloud and halo streams.

THE DESIGN of Gaia, with its two widely-spaced fields of view, and whole-sky revolving scanning, in principle allows the measurement of *absolute* parallax distances (Perryman et al., 2001; essay 172). However, even small variations of the 'basic angle' between the two fields, and in particular periodic variations caused by heating of the rotating satellite by solar radiation, can lead to variations that are degenerate with the astrometry, so leading to a *global* shift of the parallaxes.

Identified as a concern for Hipparcos by Lindegren (1977), its effect on the Hipparcos parallaxes was estimated to be negligible (Arenou et al., 1995), implying good short-term stability of its basic angle. For the much higher accuracies targetted by Gaia, the near-degeneracy between a possible basic-angle variation induced by solar heating, and a global parallax offset, is particularly problematic (Butkevich et al., 2017).

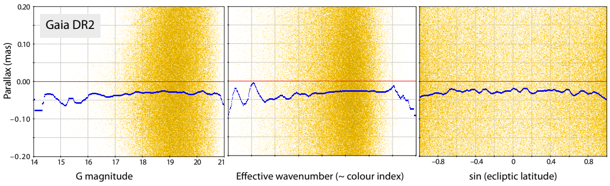
THESE CONSIDERATIONS led to the inclusion of a dedicated laser-metrology system on board Gaia (the basic angle monitor, BAM) to measure short-term variations. But due to the above degeneracies, a variation that evades measurement by the on-board metrology can only be identified by comparison with external data.

While the many quasars in Gaia's grasp offer the prospects of calibrating any global shift, higher-order effects such as magnitude or chromatic terms, a dependency on ecliptic latitude, or even temporal changes in quasar structure, demand due consideration of other external tests. I might recall that 1 μas corresponds to a Bohr radius at a distance of 10 m!

Measurements during the first year of nominal operations suggested an amplitude of the relevant Sun-aspect term ($\cos\Omega$, where Ω is the spin-phase relative to the barycentre) of amplitude 848 μas, corresponding to a parallax bias of some 700 μas (Lindegren et al., 2016). For Gaia DR1 (Gaia Collaboration et al., 2016), observations were corrected for the basic angle variations based on a simple harmonic fit to the BAM measurements.

THE SECOND data release, DR2, allowed for a more detailed analysis. From 500 000 quasars, which also define Gaia's celestial reference frame, Lindegren et al. (2018, §5.2) estimated a global parallax offset of $-29\,\mu$as. But plots versus magnitude and colour (below) reveal systematic trends of $\sim$20 μas over the relevant data ranges. The plot against ecliptic latitude furthermore shows a roughly quadratic variation, with parallaxes $\sim$10 μas smaller towards the ecliptic poles.

It is in this context that the various zero-point estimations for DR2 (see table over), dependent on population, direction, and magnitude, can be interpreted.



Lindegren et al. (2018)

STUDIES BASED on EDR3 also showed systematic offsets of a few tens of microarcseconds (Lindegren et al., 2021a). From their sample of just over 1 million quasars in the range $G = 13.4 - 21$ (although only 541 with $G < 16$), they found a weighted mean parallax of $-21\,\mu$as. They also extended their analysis to brighter sources, and a broader range of colours, using Large Magellanic Cloud stars (their §4.2), as well as the individual components of physical binaries (their §4.3).

For EDR3, the parallax bias again depends, in a non-trivial way, on magnitude, colour, and ecliptic latitude, and with different dependences for the 5- and 6-parameter solutions (their §5). They provided provisional bias functions Z_5 and Z_6 (see their Figs 21–22), to be subtracted from the catalogue value, as Python implementations at the Gaia web pages (which in turn points to the gitlab-hosted `gaiadr3_zeropoint`).

More detailed dependencies, including as a function of angular scales, are given in the description of the EDR3 astrometric solution by Lindegren et al. (2021b), while verification of the biases through comparisons with open clusters is given by Fabricius et al. (2021).

An independent treatment of the parallax bias in Gaia EDR3, also using quasars and physical binaries, and also revealing both spatial and magnitude dependences, but less so on colour, was given by Groenewegen (2021). More on the possible underestimation of the parallax errors of orbital and acceleration binary solutions is given by Nagarajan & El-Badry (2024).

DATA RELEASE 3, DR3, contains the same source list, positions, proper motions, parallaxes, and broadband photometry as EDR3 (Gaia Collaboration et al., 2023), such that *'the systematic errors present in the astrometry published in Gaia EDR3 carry over to Gaia DR3'* (their §3.3). Accordingly, the parallax bias functions Z_5 and Z_6 (and the Python implementations) noted above, apply equally to Gaia DR3 as well as EDR3.

These bias functions have since been widely used in detailed studies (e.g. Eastman et al., 2023; Fouesneau et al., 2023; Li et al., 2023; Sanders, 2023; Wang et al., 2023; Elliott et al., 2024; Naik & Widmark, 2024; Valle et al., 2024; Stoop et al., 2024, amongst many others).

I HAVE LISTED in the table opposite some of the other community-led investigations into the parallax systematics, divided into studies based on EDR3 or DR3 (even though their *astrometric* content is the same).

Investigations include binary stars (El-Badry et al., 2021); eclipsing binaries (Ren et al., 2021; Stassun & Torres, 2021); seismology (Zinn, 2021; Khan et al., 2023); and globular clusters (Vasiliev & Baumgardt, 2021; Maíz Apellániz et al., 2021). Some studies are particularly detailed, some are with respect to the EDR3 prescriptions, and so not easy to characterise with a single offset value.

Data Release/Reference	Source sample	$\Delta\varpi$ (μas)
Gaia DR1 (Sep 2016):		
Arenou et al. (2017)	DR1 validation	–40
Gaia DR2 (Apr 2018):		
Lindegren et al. (2018)	DR2 astrometry	–29
Arenou et al. (2018)	DR2 validation	–70/–20
Brown et al. (2018)	quasars	–29
Groenewegen (2018)	Cepheids	–49
Riess et al. (2018)	Cepheids	–46
Ripepi et al. (2019)	Cepheids	–70
Muraveva et al. (2018)	RR Lyrae	–57
Layden et al. (2019)	RR Lyrae	–42
Shao & Li (2019)	globular clusters	–28
Stassun & Torres (2018)	eclipsing binaries	–82
Graczyk et al. (2019)	eclipsing binaries	–31
Sahlholdt et al. (2018)	seismology (dwarfs)	–35
Hall et al. (2019)	seismology (red clump)	–41
Khan et al. (2019)	seismology (giants)	–50
Zinn et al. (2019)	seismology (giants)	–53
Leung & Bovy (2019)	distances (APOGEE)	–52
Chan & Bovy (2020)	red clump (APOGEE)	–48
Schönrich et al. (2019)	radial velocity kinematics	–54
Xu et al. (2019)	VLBI (astrometry)	–75
Lindegren (2020)	VLBI (radio stars)	–76
Xu et al. (2021)	VLBI (radio stars)	–75
Gaia EDR3 (Dec 2020):		
Lindegren et al. (2021a)	EDR3 parallax study	–94/+36
Fabricius et al. (2021)	EDR3 verification	–
Groenewegen (2021)	quasars/binaries	–
Riess et al. (2021)	Cepheids	–24
Molinaro et al. (2023)	Cepheids	–22
Molnar et al. (2022)	Cepheids/RR Lyrae	–
Kovacs et al. (2021)	RR Lyrae	–20
Maíz Apellániz et al. (2021)	globular clusters	–
Maíz Apellániz (2022)	clusters/LMC/SMC	–
Huang et al. (2021)	red clump (LAMOST)	–26
Ren et al. (2021)	eclipsing binaries	–29
Stassun & Torres (2021)	eclipsing binaries	–37
Zinn (2021)	seismology: giants	–
Flynn et al. (2022)	open clusters	–
Wang et al. (2022)	giants (LAMOST)	–28
Ding et al. (2021)	X-ray bursters	–
Bobylev (2022)	radio stars (VLBI)	–22
Khan et al. (2023)	seismology: red clump	–
Gaia DR3 (Jun 2022):		
Groenewegen (2023)	orbital parallaxes	–
Ding et al. (2024)	Galactic plane sources	–
Andriantsaralaza et al. (2022)	AGB/maser (VLBI)	–77

Studies without a simple numerical value for $\Delta\varpi$ are shown '–'.

In a study of 200 nearby AGB stars, Andriantsaralaza et al. (2022) found a large offset of $-77\,\mu$as, and suggest that the DR3 parallax errors are underestimated by a factor 5.4 for the brightest ($G < 8$ mag), and 2.7 at $G = 8 - 12$.

Several studies (of course) identify individual parallaxes that are particularly suspect, often related to their unmodelled multiplicity. One of many examples is the nearby 19.5-yr binary system GJ 67AB (Torres, 2022).

I WILL FINISH with the application of Benford's law (see essay 146) to the specific case of Gaia DR2 by de Jong et al. (2020). They showed that the 1.3 billion observed parallaxes in Gaia DR2 closely follow Benford's law: those with a parallax starting with digit 1 are five times more numerous than those starting with digit 9. The agreement is marginally affected, albeit adversely, by the inclusion of any plausible zero-point correction.