
159. Improved solar system astrometry

GAIA DATA RELEASE 3 was issued in June 2022, and the next major release, DR4, is not scheduled until 2025. But on 10 October 2023, the Gaia Data Processing and Analysis Consortium (DPAC) published five papers forming part of a special 'Focused Product Release'. I looked at the first two in essays 157 and 158.

The third, by David et al. (2023), concerns the epoch astrometry and orbit re-construction for 157 000 asteroids. I will explain how the data in this study differ from earlier releases, and summarise their main results.

I DESCRIBED THE observational principles of solar system objects in essay 64. Briefly, and in common with stars and other point-like images, sources are detected as they enter Gaia's two fields of view (as the satellite scans the sky) as long as they are brighter, at each specific observation epoch, than the detection limit.

As foreseen in the mission's early studies, the multi-epoch astrometry of all objects brighter than 20–21 mag would yield a deep and uniform detection of minor planets and other bodies (including near-Earth asteroids and Kuiper belt objects), permitting profound studies of their dynamics, structure, and taxonomy.

This is important because these minor bodies retain a record of the conditions in the proto-solar nebula, and their properties can therefore provide great insights into the formation and evolution of our solar system.

FOR SOLAR SYSTEM objects, DR2 (April 2018) was based on 22 months of observations (July 2014–May 2016), and provided limited data on around 14 000 asteroids. EDR3 provided no further updates.

DR3 (June 2022, essay 76) was based on 34 months of observations (July 2014–May 2017), and provided astrometry for 158 000 solar system objects, orbits for 154 787, and BP/RP reflectance spectra for 60 518.

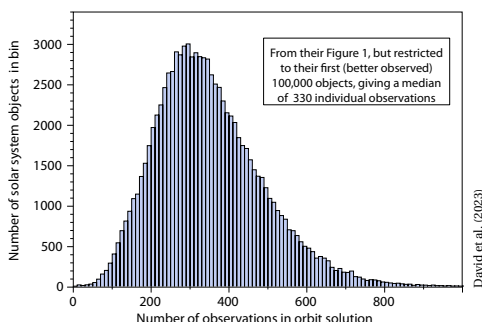
Orbit determination based on DR3 was described by Tanga et al. (2023), who also gave a summary of the associated photometric and spectral data. There is no further discussion of the photometric and spectral data in this latest 'Focused Product Release'.

IN THIS CONTEXT, the work reported by David et al. (2023) treats the *same* 157 000 asteroids as in DR3, but with a much greater observational time coverage: being 66 months, compared with the 34 months of DR3. In fact, the 66-month coverage corresponds to the time interval being used for DR4, whose full release is only expected in late 2025.

Importantly, this new data set covers more than a full orbital period for the majority of objects, and this critical time coverage results in a transformational improvement in the accuracy of the orbit reconstruction.

The terminology used here to describe an observation, or observation epoch, merits clarification. A passage or transit across one of the two Gaia fields of view comprises (a maximum of) nine position measurements at CCD level, together referred to as an (elementary) 'observation'. The nature of the satellite scanning law is such that a (varying) number of successive transits generally occurs within a 1–2 day period, followed by a gap of (typically) several weeks before the start of a new period. The clustered observations within such a visibility period are considered to define an observation 'epoch'.

THE 100 000 OBJECTS best observed in the sample of David et al. (2023) have a median of 330 elementary observations over the 66 month period, corresponding to an average of around 30 ± 10 visibility periods or epochs. The range of distinct epochs, and the orbit coverage (averaging about 1.2 orbital periods for the best-observed), strongly influences the orbit accuracy.



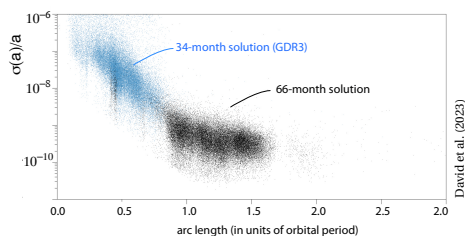
THE OTHER factor strongly influencing the final orbit accuracy is the (along-scan) accuracy of the elementary observations, which is better than 1 mas for $G < 18$ mag, degrading to ~ 10 mas at $G \simeq 20$. Compared to historical ground-based observations, often over more than a century, the Gaia observations are of unprecedented accuracy and homogeneity, and reasonably densely sampled, but extend over a limited duration that is, nonetheless, sufficient to allow good orbit fitting.

I should emphasise that, as in GDR3, the study considers only those asteroids with known (elliptical) orbits; the orbit determination of new discoveries are made within another dedicated ‘pipeline’ (Carry et al., 2021).

FOR THE ORBIT DETERMINATION, heliocentric positions are computed from numerical integration within the solar system model INPOP19a (Fienga et al., 2019), which considers the Earth–Moon barycentre with the seven other planets, the dwarf planet Pluto, a selection of 343 asteroids, and the ten most massive trans–Neptunian objects (TNO).

Mutual asteroid perturbations can be significant. In contrast to other major databases of asteroid orbits (including JPL and the Minor Planet Center, MPC), these are not yet included in the present orbit solutions.

Orbit fitting for each asteroid, determined as a least-squares fit to the Gaia data, results in the published 6-d ‘state vector’, which specifies the initial conditions (viz. heliocentric position and velocity vectors within the ICRF reference frame) at the epoch corresponding to the midpoint of the observations. All times are referred to TCB (Barycentric Coordinate Time).



This figure shows the formal uncertainty of the semi-major axis, σ_a/a , as a function of the arc length, for the current 66-month solution (black dots) and the earlier 34-month GDR3 solution (blue). The improvement once the observations cover a full orbit is clearly visible.

WHILE THE TRANSFORMATION from state vector to the more usually published (unperturbed) ‘osculating elements’ is considered routine in celestial mechanics, the unprecedented accuracies of Gaia highlight the fact that there is, as yet, no agreed transformation from the ICRS reference *system* to the ecliptic reference system. The issue is a complex one (their Section 4.6), and potentially complicates a rigorous comparison between the Gaia orbits and those from say, JPL or MPC.

THE STUDY by David et al. (2023) includes a detailed discussion comparing the 66-month Gaia orbits with the best existing orbits published by JPL and the Harvard Minor Planet Center (MPC).

They focussed on comparing the resulting semi-major axis which, in contrast with the angular Keplerian parameters, has the merit of being a true geometric quantity that is independent of the reference frame.

They concluded that, despite the different observation sets, their time coverage, and their detailed differences in dynamical modelling, there is an impressive consistency between the various solutions. In particular, they demonstrated systematic relative differences in semi-major axis, σ_a/a , that are below 5×10^{-10} .

ANOTHER WAY of confirming orbit accuracies is to use stellar occultations observed from Earth.

Occultations events are, today, predicted on the basis of stellar astrometry from Gaia (essays 24, 137). But a test of the orbit accuracies of solar system objects can be made by comparing the 66-month orbits with the timings of successful occultations. Their test sample comprised 978 main-belt asteroids, associated with 5774 astrometric occultation measurements.

The observed minus computed (O–C) values showed a large spread, reaching several hundred milliarcsec. But when only occultation events contemporary with the Gaia mission were selected, the residuals were much smaller, peaking at ~ 10 milliarcsec, and with a substantially suppressed tail of high values.

THE NEXT MAJOR improvements to these existing orbits will come from the combination of the larger number of observations, and the extended arc length, of the approximately 10-year DR5 solution, whose release is expected around 2030.

This will essentially double the time interval of the 66-month data used by David et al. (2023), further improving the accuracy of the orbit determination of small solar system bodies. They anticipate, for example, that the final accuracies of the Trojan orbits will then be as good as those of the main-belt asteroids today.

AMONGST THE ‘visualisations’ of Gaia Sky (essay 147), I referred to some of those constructed from earlier data releases which illustrate, powerfully and visually, the direction of this work. For example, this [tour through the asteroids](#) is based on DR2. These [orbits of 154 741 asteroids](#) are based on DR3, colour-coded according to (reflectance) colour, which serves as a proxy for chemical composition. Objects are clearly resolved into the main-belt asteroids, Mars crossers, Jupiter Trojans, near-Earth objects, and the brightest 24 trans–Neptunian objects.

This recent Gaia Sky video illustrates the remarkable precision of the new Gaia Focused Product Release, based on the [asteroid 18520 Wolfratshausen](#).