27. The Celestial Reference Frame

Classical astrometry from the ground, up until the Hipparcos catalogue publication in 1997, could only measure positions – and parallaxes – with respect to other stars nearby on the sky. Even the $6^\circ \times 6^\circ$ Schmidt plates used for the grand photographic sky surveys of the second half of the 20th century, and later HST in space, could only make these relative measurements.

Piecing the measurements together, to form the best global reference network, always left local distortions which varied across the sky. Even the best star positions were found to have systematic errors of 0.2–0.3 arcsec once the Hipparcos reference frame became available.

But what were these measurements referenced to in the first place? What defines the origin of a stellar reference system? Although the details are intricate, the principles are straightforward, and analogous to the geographical framework of longitude and latitude used to define locations on the Earth's surface. In this equatorial coordinate system, astronomers agree on an origin for 'right ascension' (the equivalent of longitude) and for 'declination' (the equivalent of latitude).

The origin of right ascension was chosen long ago, by Hipparchus around 130 BCE. This 'First Point of Aries', or 'vernal equinox', is one of the two points on the celestial sphere at which the celestial equator (the imaginary circle in the same plane as Earth's equator) crosses the ecliptic (Earth's orbital plane around the Sun). In the same way, declination is defined with respect to the Earth's equator, north and south from 0 to $\pm 90^\circ$.

The problem gets more complicated because the Earth's spin axis is not inertially fixed in space, but rotates slowly westward about the poles of the ecliptic, completing one sweep in 26 000 years. This 'precession' causes the equatorial coordinates of celestial objects to change continuously, by about 1° in right ascension over 70 years. The problem is further compounded by the shorter term effects of 'nutation' and 'polar motion'.

This led to the choice of reference systems which were revised, every few decades, by adjusting the epoch at which the Earth's coordinate system was specified. Thus, over the past 200 years, astronomers have used reference systems which were successively specified by the Besselian epochs B1875, B1900, and B1950, and more recently the Julian epoch J2000. Within any such system, the star position itself also changes (due to its proper motion) according to when it was measured.

As position measurements improved, the complex motion of the Earth introduced effects which were increasingly difficult to explain, and to account for.

These wobbling terms include not only the Sun and Moon's gravitational torques of precession and nutation, but a whole host of complex effects responsible for polar motion: some internal to the Earth, others forced by climatic and seasonal changes due to oceans, tectonic plate motions, and many others.

This led, in turn, to efforts to construct a 'dynamical reference system', linked to the observed motion of solar system bodies, whose orbits around the Sun should be largely decoupled from the motion of the Earth.

By the 1990s, radio VLBI measurements became possible, for a few dozen radio stars and quasars, at higher accuracies than were possible using optical measurements from the Earth. In consequence, the celestial reference system adopted by the International Astronomical Union moved to one defined at radio frequencies and, in particular, one tied to distant quasars which better represented the ideas of an inertial reference system, decoupled from the Earth's wobbling motion.

By making positional measurements from space, Hipparcos and Gaia achieve vastly improved accuracies from above the Earth's perturbing atmosphere. At the same time, measurements from a space platform means that they were, at a stroke, freed from the hugely complicating effects of the Earth's spin-axis motion.

A further central technique used by both Hipparcos and Gaia is their two widely-separated fields of view on the sky, which are superimposed in a common focal plane. As set out by Pierre Lacroute in his first ideas for space astrometry in 1968, and further developed by Lennart Lindegren in the 1970s, a carefully chosen angle between the two – one which is not a simple rational fraction of 360° (Hipparcos used 59°, Gaia used 106°), leads to an extremely rigid reference frame over the entire sky. The consequences are far reaching, in that the parallax of every star is 'absolute'. In other words, a star's parallax is no longer defined relative to that of another; each has the same 'offset', or zero-point, as every other.

TWO PROBLEMS remain. The first is to establish the zero-point of this parallax scale. The second is related, and particularly awkward: it turns out that, as the satellite scans the sky, any tiny changes in the angle between the two viewing directions (specifically, if phased with the sixth harmonic of the spin frequency) the resulting effect is indistinguishable from a common offset in the parallax zero point.

Unfortunately, this is precisely the effect that results from the Sun's changing illumination acting on the spinning satellite. Many details of the instrument design, both for Hipparcos and for Gaia, were driven by efforts to decrease this dependency, but the fact remains: any tiny changes in this angle can propagate through to a tiny shift in the zero-point of the totality of parallaxes.

AS THE DEFINITION of the Hipparcos observing programme took shape in the early 1980s, plans were put in place to include stars that could be used, once the catalogue was finalised, to link the rigid reference frame defined by its 120 000 stars to an extragalactic 'inertial' reference framework, and in the process estimate and correct for any tiny offset in the parallax zero-point.

The goal was, in other words, to determine the global orientation and rotation (or spin) of the coordinate frame defined by the Hipparcos positions with respect to extragalactic sources. The big difficulty was that, because of its limiting magnitude of about 12 mag, only one quasar, 3C 273, could be included in the observing programme, and even that was so faint that it contributed very little to the final link.

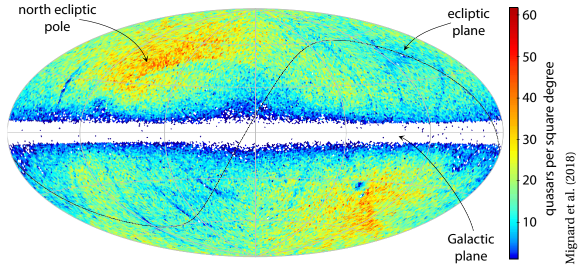
The effort required to establish this link was substantial. And to achieve it, the contributions of several groups over a number of years, and using a variety of less direct techniques, were essential (Kovalevsky et al., 1997).

These indirect methods included interferometric observations of radio stars by radio interferometry (VLBI, MERLIN and VLA); observations of quasars relative to Hipparcos stars using CCDs, photographic plates, and Hubble Space Telescope; photographic programmes to determine stellar proper motions with respect to extragalactic objects; and a comparison of Earth orientation parameters obtained by VLBI and others.

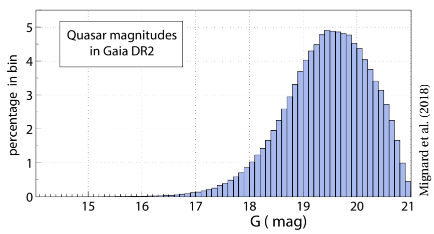
Combined and suitably weighted, the coordinate axes of the published catalogue were finally believed to be aligned with the extragalactic radio frame to within ±0.6 mas at the mid-catalogue epoch J1991.25. And it was estimated to be 'non-rotating' with respect to distant extragalactic objects to within ±0.25 mas/yr.

THE PROBLEM IS as central to Gaia as it was for Hipparcos, and the accuracy for the link correspondingly more demanding. But there is one very big difference: Gaia's limiting magnitude, at 20–21 mag, allows very large numbers of quasars, all across the sky, to be observed by the instrument itself. And this means that the problem can be tackled much more directly.

The challenge was considered in depth during the mission's feasibility study before its selection in 2000. Studies then indicated that some 500 000 quasars would be observable directly by Gaia, with a mean density on the sky of about 25 per square degree. Issues of sky uniformity, colour dependency, and possible small structural changes in position were all considered.



The second release of Gaia GDR2 contains the positions of 556 869 quasars, extending to $G = 21$ mag, and defining a kinematically non-rotating reference frame in the optical (Mignard et al., 2018). A subset have accurate VLBI positions allowing the reference frame axes to be aligned with the International Celestial Reference System (ICRF) radio frame.



Median positional uncertainties are 0.12 mas for $G < 18$, and 0.5 mas at $G = 20$. Large-scale systematics are in the range 20–30 μas. The optical positions for a subset of 2820 sources in common with the ICRF show very good overall agreement with the radio positions.

SO ALREADY IN 2018, based on less than 40% of the data from the nominal 5-year Gaia mission, we have the first realisation of a global, non-rotating optical reference frame that meets the ICRS prescriptions, being built only (and directly) on extragalactic sources. Its accuracy matches that of the current radio frame of the ICRF – but with a much higher density of sources.

And such an accurate reference frame may have cosmological implications previously considered unimportant and unmeasurable, such as detecting the tumbling of a triaxial dark matter halo (Perryman et al., 2014).