213. Telescope calibration/pointing: 1

Gaia is making substantial contributions to the improved calibration and pointing of ground- and space-based telescopes. There are, however, few published descriptions of these sorts of applications.

Before detailing some of these developments with Gaia in my next essay, in part based on inputs from various observatories, I will look here at what is now largely consigned to history – how the first space astrometry positions from Hipparcos were applied to the calibration of photographic plates and meridian circles.

Astrometric measurements naturally divide into two broad categories. *Narrow-field* instruments, providing relative measurements over not more than a few degrees, include photography, CCD imaging, adaptive optics, speckle interferometry, and phase-referencing radio interferometry. *Wide-field* or semi-global techniques include meridian circles or transit instruments, astrolabes, optical phase interferometers, Michelson interferometry, radio interferometry including VLBI, and the satellites Hipparcos and Gaia.

Photographic and CCD instruments are further categorised, according to focal length, image scale, and field of view, into classical astrographs (as used for the early Carte du Ciel project), Schmidt telescopes which extended the field of view by compensating for spherical aberration, and long-focus instruments yielding a larger scale – originally based on refractors to provide better mechanical stability, but subsequently using reflectors. Later astrographs, e.g., those at Lick and Yale, had fields around 4 – 5°, while the USNO Twin and Hamburg Zone Astrographs had fields of around 9°.

The main challenge for wide-field or semi-global astrometry is the measurement of large angles, and in the provision of a fundamental system in the absence of any other reference frame. For several centuries, and until the end of the 20th century, the basic instrument was the meridian circle: a combination of a transit instrument and a vertical circle, from which the right ascension was deduced from the local sidereal time and the declination from the zenith distance at the time of meridian transit.

The use of photography to determine star positions began around 1870, flourished with the immense international cooperation of the Carte du Ciel (e.g. Debarbat, 1988; Urban & Corbin, 1998; Jones, 2000), and remained a fundamenal astrometric technique almost until the end of the 20th century. Schmidt telescopes, from the 1930s onwards, also had astrometry as their main objective. Such surveys were only superseded, from the 1990s, by ground-based digital surveys. In parallel, fast and accurate measuring machines and associated reduction software were developed (e.g. Kovalevsky, 2002).

In the reduction of photographic plates, the transformation between the celestial sphere, and the xy domain of a set of plate measurements, is generally a one-to-one vector transformation. But this must account for many factors: orientation of the plate axes, plate tilt and centre, scale factor, gnomonic projection, coma and field curvature, distortion, astigmatism, differential atmospheric refraction, chromatic aberrations, and magnitude equation, i.e. positional errors as a function of magnitude (e.g. Eichhorn & Williams, 1963; Kiselev, 1989; Brosche et al., 1989; Bienayme, 1993).

Before Hipparcos, an insuperable obstacle was the absence of a sufficiently accurate *and* dense stellar reference frame – both properties were necessary. A high-accuracy reference framework was required to exploit the intrinsic plate accuracy, of typically 0.1 arcsec or a little better, while a high reference star density was needed to model behaviour more complex than, say, a third-order polynomial in x and y.

This changed with the availability of the Hipparcos and Tycho Catalogues in 1997, with the accurate proper motions also ensuring that a high-accuracy reference frame could be propagated over half a century or more.

As a result, the subsequent decade saw a substantial effort from groups who re-reduced, and in many cases also re-measured, a wide variety of plate material obtained during the entire 20th century, as well as meridian circle observations, and data from other classical astrometric instruments (e.g. Vondrák et al., 2000).

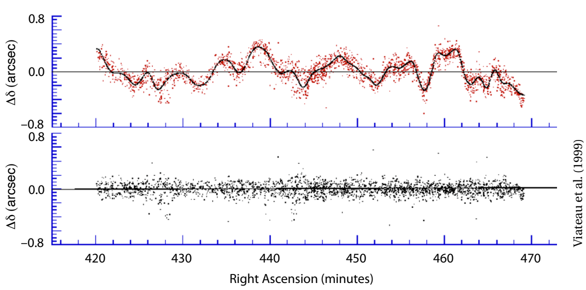
I WILL GIVE just a few examples of these re-calibration efforts, referring the interested reader to Perryman (2009, Chapter 2) for further details.

Early application to the Bordeaux and La Palma automatic meridian circles replaced the previously used FK5 catalogue positions with those from Hipparcos (Requieme et al., 1995; Argyle et al., 1996). This resulted in *'a remarkable improvement in the post-fit residuals'*, with standard deviations falling from around 0.2–0.3 arcsec to around 0.02–0.05 arcsec in both coordinates.

Many such re-calibration efforts, and very extensive catalogues, were derived in this way. But the availability of the Hipparcos reference frame rapidly made classical visual meridian instruments obsolete, and several automatic circles were subsequently closed down. However it was demonstrated at Flagstaff (Stone et al., 1996) that, equipped with a CCD detector, and working in drift-scan mode, meridian circles could give internal errors of less than 50 mas to $V = 15 - 16$ mag, based on bright reference stars from the Hipparcos and Tycho Catalogues.

Plans to equip other meridian circles with CCDs were followed up at Bordeaux (Viateau et al., 1999), Mykolaiv (formerly Nikolayev) in Ukraine (Pinigin et al., 1997), Valinhos at São Paulo (Lopes et al., 1999), and the San Fernando (Cádiz) instrument at El Leoncito in Argentina (Muiños et al., 2002). The Carlsberg Meridian Telescope at La Palma (formerly the Carlsberg Automatic Meridian Circle) proved particularly productive in extending the magnitude limit to (Sloan) $r' = 17$ mag (Evans, 2001; Evans et al., 2002), although the instrument was also finally decommissioned in 2013.

In another example, the US Naval Observatory pole-to-pole catalogue $W2_{J00}$ (Rafferty & Holdenried, 2000) was constructed from observations between 1985–1996 using two transit circles, one located in Washington DC (the six-inch circle, operated there since 1897), and the other in Blenheim, New Zealand (a seven-inch circle, originally operated since 1948 from El Leoncito, Argentina). The authors commented: *'This project is the latest and largest of a long series of transit circle catalogues produced by the US Naval Observatory. It is also, because of advancing technologies, certainly the last'*.

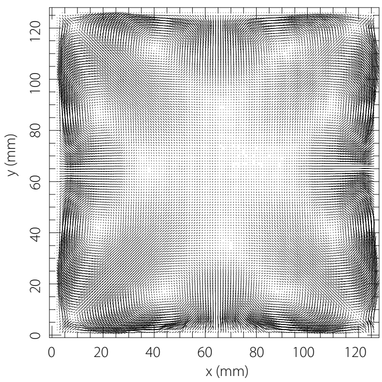


Top: residuals between a Bordeaux meridian circle strip and the mean catalogue positions from Hipparcos/Tycho, showing the best-fit B-spline. Bottom: after subtraction of the B-spline.

THE RE-CALIBRATION of photographic plates using Hipparcos positions was also pursued extensively, creating catalogues of positions and proper motions for large numbers of stars down to the plate limits.

Early re-reductions of Schmidt plates using the Hipparcos/Tycho data (Robichon et al., 1995) were followed by many plate digitisation and reduction efforts (e.g. exploiting the early Palomar POSS and later SERC plates) using the APM, APS, DSS, and SuperCOSMOS measuring machines, leading to (amongst others) the Digitised Sky Survey and the Guide Star Catalogue (GSC) for HST operations, with GSC II comprising 945 million stars (Robichon et al., 1995; Lasker et al., 2008).

Other substantial catalogues subsequently placed on the Hipparcos reference frame included the USNO A1 (Monet & Corbin, 1997), USNO A2 (Assafin et al., 2001), and USNO B1 (Monet et al., 2003) catalogues, and the early epoch AGK2 (Zacharias et al., 2004), CPC2 (Zacharias et al., 1999), and Lick NPM (Hanson et al., 2004) and SPM (Girard et al., 2004) catalogues.



Fixed-pattern astrometric residuals for the first-epoch Palomar POSS O survey plate, reduced to the Hipparcos reference system, at 18 mag. The pattern is very different for bright stars (Monet et al., 2003).

A related and extensive topic, which I can only touch on here, is the use of Hipparcos in the re-calibration of the Astrographic Catalogue (to 11.5 mag, and completed in the first quarter of the 20th century), and the related but deeper (to 14 mag) Carte du Ciel plates, started in 1891 and finally completed only in 1950.

This huge undertaking started with a machine-readable version (Kuzmin et al., 1999), with 22 separate zones yielding the 4.6 million star Astrographic Catalogue at mean epoch 1907: AC2000 (Urban et al., 1998b; Urban et al., 2001). Two parallel efforts combined these first epoch measurements with the Tycho Catalogue: the TRC (Høg et al., 1998) and the ACT (Urban et al., 1998a), all eventually superseded by the Tycho 2 Catalogue of 2.5 million stars (Høg et al., 2000a; Høg et al., 2000b).

GAIA'S DEPTH and accuracy is such that re-analysis of old photographic and meridian circle observations provides little new astrometric information, and I am not aware of any such treatments. But as I will show in the next essay, Gaia does play a very important role in today's instrument calibrations and telescope pointing.