Contribution to the history of astrometry No. 8 25 November 2008

Invited contribution to the symposium at ESTEC in September 2008:
**400 Years of Astronomical Telescopes: A Review of History, Science and Technology**
Proceedings will be edited by B. Brandl et al.

# 400 Years of Astrometry: From Tycho Brahe to Hipparcos

*Erik Høg, Niels Bohr Institute, Copenhagen*

ABSTRACT: Galileo Galilei's use of the newly invented telescope for astronomical observation resulted immediately in epochal discoveries about the physical nature of celestial bodies, but the advantage for astrometry came much later. The quadrant and sextant were pre-telescopic instruments for measurement of large angles between stars, improved by Tycho Brahe in the years 1570-1590. Fitted with telescopic sights after 1660, such instruments were quite successful, especially in the hands of John Flamsteed. The meridian circle was a new type of astrometric instrument, already invented and used by Ole Rømer in about 1705, but it took a hundred years before it could fully take over. The centuries-long evolution of techniques is reviewed, including the use of photoelectric astrometry and space technology in the first astrometry satellite, Hipparcos, launched by ESA in 1989. Hipparcos made accurate measurement of large angles a million times more efficiently than could be done in about 1950 from the ground, and it will soon be followed by Gaia which is expected to be another one million times more efficient for optical astrometry.

## Introduction

The prospects for astrometry looked bleak at the middle of the 20$^{th}$ century. If an astrometrist retired the vacancy was usually filled with an astrophysicist, and astrophysics was moving towards the exciting new extragalactic astronomy. But I did not feel any pressure from this trend when I studied in Copenhagen (1950-56) where both my teachers at the observatory, Bengt Strömgren and Peter Naur, were very familiar with astrometry, and it was natural to follow their advice. As a boy, I had read about Tycho Brahe and Ole Rømer, the two Danish heroes in astronomy, who both in fact worked on what is now called astrometry. Astrometric catalogues on the library shelves like the Albany General Catalogue (GC), the AGK2, and the Jenkins catalogue of parallaxes attracted me, though I did not of course know that 40 years later I should lead the construction of the Tycho-2 Catalogue (Høg et al. 2000). This catalogue has replaced all previous reference catalogues with its positions and proper motions derived from observations with the Hipparcos satellite and 100 years observations with ground-based telescopes. This presentation is focused on optical astrometry over the past 400 years. More details about the recent history of astrometry are given in (Høg 2008a, b, and c).

The term astrometry does not apply to astronomical measurement in general as the word suggests, but only to the measurement of positions on the sky of stars and other celestial objects. The position of a star changes with time due to its proper motion, to the parallactic motion created by the motion of the Earth around the Sun, and to the orbital motion in the case of a binary star. The radial velocity of a star along the line of sight as measured by the shift of lines in the spectrum is the third component of the space velocity, which is needed for many applications, but it does not belong to astrometry. It should be noted that the radial velocity can affect the proper motion of nearby stars to such extent that accurate measurement of the radial velocity can be obtained from observations of positions over long intervals of time, according to e.g. Lindegren et al. (2000). The term astrometry came into use to distinguish it from astrophysics, especially after the introduction of stellar spectroscopy 150 years ago and of atomic theory later on, which were used to analyse the spectra. For the two millennia prior to that, astrometry had in fact been the main task of astronomy. Astrometric observational data have been the basis for a deep astronomical understanding of stars, star systems, planetary motions, and the underlying physical laws.

I will follow the history of astrometric instruments from the introduction of telescopic sighting and wire micrometers in the 17$^{th}$ century, via the transit instrument and the meridian circle in the 18$^{th}$ to photographic astrometry in the late 19$^{th}$ and photoelectric astrometry in the 20$^{th}$ century, including satellite astrometry, and finally CCD detectors. Some of the main astronomical results obtained by optical astrometry during the centuries will be outlined.

Today, positions and proper motions are given as celestial coordinates in the main astrometric reference system which is the International Celestial Reference System (ICRS). This system, adopted by the International Astronomical Union, is defined by the radio positions of 212 quasars, supposed to have negligible proper motions. It is represented in the optical by positions and proper motions in the Hipparcos Catalogue, officially called the Hipparcos Celestial Reference Frame (HCRF). ICRS is a coordinate system in right ascension and declination (RA and Dec) very close to the previous adopted system which was called J2000.0. Tycho Brahe used a system of ecliptic longitude and latitude. Later on RA-Dec systems tied to the Earth's rotation axis were used although the change with precession and nutation had to be taken into account. With the adoption of the ICRS for all catalogues the astronomical application of catalogues is simplified since precession and nutation only need be taken into account in connection with the pointing of ground-based telescopes as a computed coordinate transformation. The transformations are computed by means of vectors, no longer by spherical trigonometry as was usual some thirty years ago.

The history of other aspects of astrometry deserves equal appreciation. Such aspects are mathematical methods of data reduction, computing techniques, electronic control of instruments, electronic data acquisition, accurate clocks, and machines for measuring photographic plates, but these could not be included here. Briefly, however, on computing: Tycho Brahe had used a method called *prosthaphaeresis,* which had been invented by the Arab mathematician Ibn Jounis in the 11$^{th}$ century. It replaced multiplication with the addition of trigonometric functions. Logarithmic tables came into use after they had been introduced by John Napier in 1614 and had been enthusiastically supported by Kepler. In the subsequent period of over 300 years astronomical formulae were developed in logarithmic form to facilitate calculations, and books appeared with logarithms of seven and more decimals of trigonometric and many other functions. The time of logarithms had run out about 1950. We had used logarithms in school, but we were using mechanical and electrical calculators in astronomy in the 1950s. The first electronic computer, an IBM 650 with punched card in- and output, came to Copenhagen in 1954 and I took a programming course. Already two years earlier Peter Naur had told of his experience with the electronic computer EDSAC in Cambridge at a lecture in the university. The room was overfull, I was sitting with others on the floor, and even Niels Bohr had come to listen and to wonder at the fantastic punched tapes with rows of holes for numbers, which Naur rolled out on the floor and then gave us freely. I was soon engaged to interpolate in Naur's ephemerides of the minor planet 51 Nemausa computed with EDSAC, using Leslie Comrie's interpolation tables and a mechanical calculator.

## Tycho Brahe's legacy: Instruments and Newton's theory

Tycho Brahe had set a new standard for astronomical measurements by his twenty years of work on Hven. He improved the then classical instruments, the sextant and the quadrant, to give positions of stars with errors some five times smaller than those of his contemporary colleague Wilhelm of Hesse, i.e. about one minute of arc. Tycho made many improvements and had the means to carry them out thanks to a lavish support by the Danish king, Frederik II. The king wanted to promote science and saw that Tycho Brahe complied with this ambition. Tycho received the island of Hven close to Copenhagen in 1572 and then enjoyed a support equivalent to one or two per cent of the king's annual income, altogether the value of “a barrel of gold”. With this basis he could make instrumental improvements and obtain observations in amounts and qualities never seen before.

Tycho had learned from his experience with the large quadrant, which he built in Augsburg 1570, that size alone was not a safe way to better accuracy. The quadrant was not stable, exposed to rain and wind as it stood, and it tipped over in a storm after a few years. Moderate size would lead to more accurate manufacture which was another of Tycho's achievements. For instance, on Hven he developed the sighting device slits-and-plate (Fig. 1) which became the preferred tool for his followers until the telescopic sight could take over in about 1660.

In Danzig, Johannes Hevelius (1611-1687) continued to use the slits-and-plate sighting device until his observatory was destroyed by fire in 1679. His observations, accurate to about 15”-20”, could compete easily with any of the early telescopic observations, and were not seriously rivalled until Flamsteed and Rømer had developed their own observing techniques after Hevelius' death (Chapman 1990).

Tycho left a catalogue with positions of 1000 stars, the same number of stars as in the famous catalogue of Ptolemy. It remained unsurpassed for a century, until Hevelius' catalogue with 1564 stars appeared posthumously in 1690. Tycho's observations of the planets, especially of Mars, came to make the strongest impact on science and civilization. Johannes Kepler derived the three famous laws of planetary motion: about the elliptical form of the orbits, the speed in the orbit, and the size and period of all orbits in the system of planets. The three laws, completed in 1619, found an explanation in Isaac Newton's *Principia* of 1687 in terms of the universal gravitational attraction between masses and the laws of mechanics concerning force, velocity, and acceleration. These laws became the basis for the subsequent theories of celestial mechanics for planets and satellites, and for the technical revolution with engineering of machines and buildings.

## 17$^{th}$ century: Telescopic sight

The Galilean telescope magnified the object: it increased the angular resolution beyond the several minutes of arc of the unaided eye. This enabled Galilei in 1609-10 to see mountains on the Moon, satellites around Jupiter, the changing form of Saturn, spots on the Sun, phases of

Venus, and to resolve the Milky Way into individual stars. The angular resolution opened up a new view of the physical nature of the heavens, simply by watching what you could see inside the quite small field of view. But this type of telescope was unsuited as a sighting device; it could therefore not be used in classical astrometry concerned with the measurement of large angles between stars.

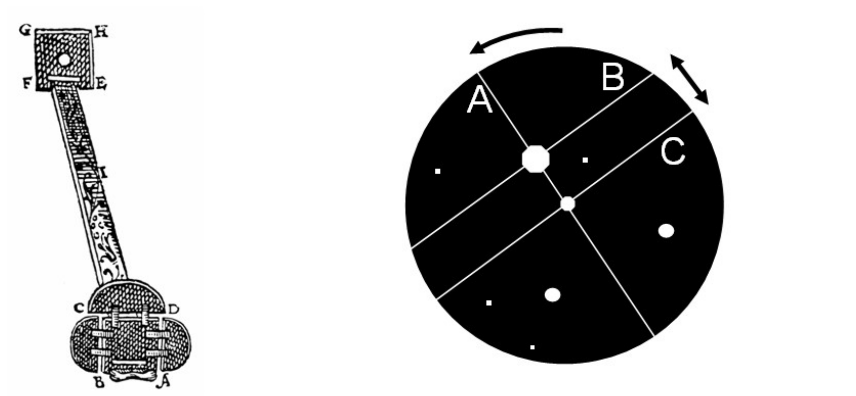


**Fig. 1 Left:** Tycho Brahe's sighting device, after 1570, slits-and-plate. **Right:** Wire micrometer, after 1660. The observer centers one of the stars on the A-C cross of fixed wires by moving the telescope. He turns the micrometer to place wire A on both stars, a scale shows the position angle. He moves wire B to the star and obtains the separation

This problem could be solved with the telescope invented by Kepler in 1611 in which a convex lens is used at the eye, instead of the concave lens in Galilei's telescope. The convex eye-lens is placed with its focus where the star images are formed by the front lens. This allows a cross hair to be placed at the common focus of the objective and the eyepiece lens, thus defining a line and then one has a sighting device. This invention was described in a letter by the English amateur astronomer William Gascoigne in 1641, in which he also tells how the cross hair can be made visible at night by illumination (Chapman 1990). Gascoigne developed the filar micrometer on the principle shown in Fig. 1, and he made a few observations in 1640 of the angular diameters of Jupiter, Mars, and Venus and of the angular separation of stars in the Pleiades cluster. But Gascoigne's work on the telescopic sight (and on the filar micrometer) fell into neglect after the inventor's death in the Civil War in 1644.

Christiaan Huygens independently invented the filar micrometer in about 1660 and made accurate measurements of the diameters of the Moon and all the planets. The invention was made independently in Italy and by 1675 the telescopic sight with a cross wire was in common use. The micrometer became a standard tool for measuring angles within the field of view during more than 300 years, manufactured in ever more accurate versions. This was the birth of s*mall-angle astrometry* which soon achieved accuracies of one second of arc and even better, while the accuracy of *large-angle astrometry* with quadrants and later on with meridian circles improved more slowly.

The regular swing of a pendulum was known to Galilei. To use it to control a mechanical clock was not simple, but Huygens succeeded in 1658. The pendulum clock in ever better versions was used by astronomers until the quartz clock could take over by 1950. An accurate clock was required in connection with observation of the transit time over the north-south meridian. In practice, the time was recorded when the star crossed one or several wires parallel to the meridian in the telescope field of view. Thanks to the regular rotation of the Earth this measurement corresponds to the right ascension coordinate of the star.

The other coordinate, the declination, could be measured when the telescope was precisely set to let the star follow a wire in the field. Reading the altitude angle of the telescope (cf. Fig. 2) on a finely divided circle was then required. The manufacturing of ever more accurate divided circles was a high art (Chapman 1990) and crucial for astrometry up to the 1990s when the reference systems of stars provided in the Hipparcos and Tycho-2 catalogues made the accurate circles virtually obsolete.

Flamsteed in Greenwich used mainly a sextant with two telescopic sights from 1676 to 1690. He then built a mural "quadrant", but of 140 degrees arc so that he could directly observe the Pole Star. This instrument served him for the Great Catalogue and the last recorded observation was made in 1719, shortly before his death.

## 18th century: Quadrants prevail

Astronomers of the new century would learn that the Earth's motion around the Sun makes all stars write an ellipse on the sky in one year and that the Earth's axis wobbles. They realized that the fixed stars are moving, that the Sun moves among the stars, and that some stars orbit each other. They learned that comets return, and a new planet, Uranus, was found. These discoveries were results of measuring and mapping the stars ever more accurately and in ever larger number, and of recording the motion of the objects in the solar system. The latter observations were studied in celestial mechanics, i.e. developments of the theory of gravitation, and the scientists were challenged by the planets, and especially by the intricate motion of the Moon.

In 1718, Edmund Halley had discovered that fixed stars are moving since he found that three bright stars had changed their position since the ancient Greeks. On the same occasion Halley stated that the stars were at least 20,000 or 30,000 times as distant as the Sun. That could be concluded from the lack of positive evidence of a parallax in the most accurate position observations of the time. Already in 1748 James Bradley could extend this lower limit to at least 400,000 times since the failure to measure annual parallax with his precision instrumentation showed that it must be less than half a second of arc.

Astronomers had been attempting to measure the annual parallax of a star since Copernicus in 1543 had proposed that the Earth orbits the Sun in one year. Bradley was one of those and had a telescope built, a zenith sector, which could measure the position of stars near the zenith. The small angles to be measured and the stable mounting gave a high accuracy about one second of arc, though only in the north-south direction. His measurements in 1725 showed a shift, but not in a direction that could be explained by the shift of the Earth relative to the Sun. Bradley gave the true explanation which was that the velocity of the Earth in its orbit causes the direction to a star to be shifted forward in the direction of the Earth velocity. This was a new effect due to the very large, but finite velocity of light which had been discovered in 1675. The effect is called aberration and amounts to 20 seconds of arc for a given star at some times of the year. This is a large amount, and aberration was taken into account in all subsequent astrometry, resulting in much better accuracy of star positions.

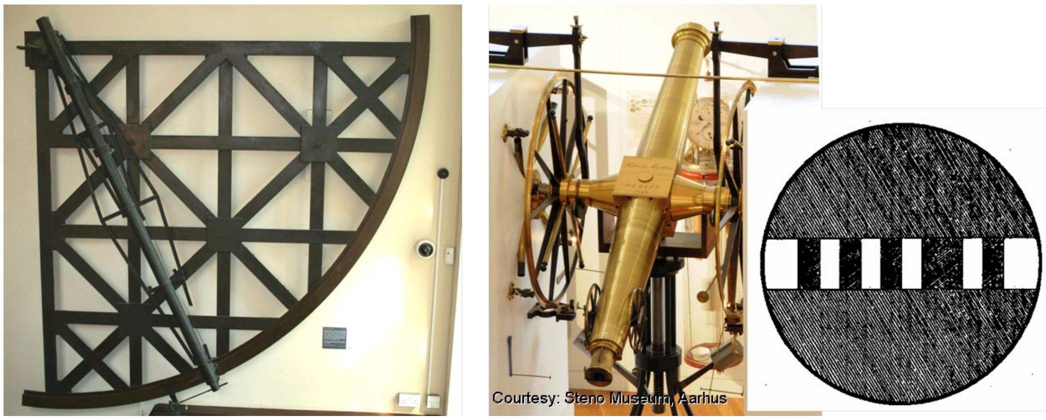


**Fig. 2** **Left:** The John Bird quadrant of 1773, Greenwich. **Right:** The Copenhagen meridian circle from 1859 and a grid used for experiments in 1925 with photoelectric recording of star transits

With the higher accuracy Bradley was able to discover a smaller effect; the stars wobble with a period of 18 years and an amplitude of nine seconds of arc. In 1748 he explained the effect as a wobble of the Earth rotation axis due to a variation of the Moon's orbit.

The quadrants were still dominating astrometric observations in the 18$^{th}$ century, but a different type of astrometric instrument was being developed. Already in 1675 Ole Rømer had introduced the transit instrument, which he set up in his Copenhagen residence in 1691. It consists of a telescope mounted perpendicularly on an axis, and the ends of the axis are placed on pivots in east and west. The telescope is pointed at a star before it crosses the meridian, and the transit time is measured, just as at a quadrant with telescopic sight. In 1704, 30 years after he had the first idea (Herbst 1996), Rømer set up a similar instrument, but now with a divided circle also mounted on the axis. Rømer introduced fixed microscopes to read the circle, thus obtaining the declination coordinate. This was *Rota Meridiana,* the meridian circle (cf. Fig. 2), which is called a transit circle in English-speaking countries, and it became the most accurate instrument for measuring large angles on the sky up until 1990. But it took a century before the meridian circles took over, for reasons explained in the following section. Rømer was motivated by the search for parallaxes and believed for a while that he had succeeded in finding one.

All Rømer's observations were destroyed in the Copenhagen city fire in 1728, except those from three nights, 20-23 October 1706, called *Triduum,* of which several copies had been made and placed at different locations. The external standard errors of the mean positions were 3.4” in RA and 4.5” in declination (Nielsen 1968). Tobias Mayer in Göttingen chose 80 of the stars from *Triduum* for re-observation and derived proper motions by comparing with Rømer's observations in 1706, with his own and with Lacaille's observations in 1750 and 1756. His aim was to see if there was a systematic motion indicating that the Sun was moving towards any specific part of the sky. In 1760 he concluded that this was not the case. In 1783, however, William Herschel concluded from the motions of only 13 stars that the Sun was moving towards Hercules. Innumerable studies of this phenomenon, the Solar Apex, and of other systematic motions of stars were to follow whenever a new set of proper motions became available. - Incidentally, William

Herschel used the motions from Mayer, without mentioning Mayer or Rømer, but only that he had the motions from a book by Jerome Lalande (F. Mignard 2008, private comm.).

Halley computed parabolic orbits of 24 comets from the preceding three centuries and in 1705 drew attention to the fact that three of them had nearly identical orbits in space and that they were therefore successive appearances of the same comet. He predicted its next return in 1758. In the popular mind comets had always been portents of disaster, while even to astronomers the nature of comets and their role in the cosmic order were still shrouded in mystery. The year came and Halley's Comet reappeared, spectacularly for everybody to see, and a triumph for astronomy, showing that the events of the world are predictable, as many in fact believed.

Bradley left the raw data of a large number of observations. They had been made from 1750 until his death in 1762 with a transit instrument for the right ascensions and a mural quadrant for the declinations. Since Bradley had carefully recorded temperatures and various calibrations the observations were considered to be very valuable and they were printed in full between 1798 and 1805. Then Friedrich Bessel took the reduction in hand and produced a good catalogue. Later in the 19$^{th}$ century A. Auwers improved the reduction further, resulting in a catalogue of over 3000 stars. Brosche & Schwan (2007) have shown by direct comparison with the Hipparcos catalogue that the uncertainty in both coordinates for a subset of 2450 entries is only 1.1 arcsec. This catalogue was used to derive proper motions even for the General Catalogue published in 1937 and for FK5 published 1988. Much larger star catalogues were published from observations later in the 18$^{th}$ century, especially the one of 50,000 stars by Jerome Lalande in *Histoire Céleste Francaise*.

William Herschel wanted to measure parallaxes and thought he could do it by measuring pairs of a bright and a faint star with his wire micrometer. Their separation would change with the time of year since the brightest star was closer to Earth than the faint one, so he believed to begin with. He knew that to measure the small separation in the field of view would be much more accurate than to measure large angles with a quadrant as others were doing. Hence he started to examine all the bright stars attentively with his 7-foot (focal length) telescope, to see whether they had faint companions nearby. On a night in 1781 he noticed a bright star that appeared larger than the others, about 4” diameter, which he could see because of the high magnification and the excellent quality of his self-made mirror telescope. He suspected it to be a comet, but it was a new planet, later called Uranus. A new planet beyond Saturn was a world sensation. It was followed by astrometric position measurements in the following years, and it was found that its position had already been measured in 1756 and 1690, but it had been taken for a star.

Herschel's survey of companions to the bright stars begun in 1779 turned out to be important in itself. The large number of cases in which bright stars had a close companion, faint or bright, far surpassed what could be expected through chance distribution of stars. This had already been pointed out in 1767 by the Rev. John Michell. Herschel soon thought of these stars as real binary systems. Twenty years later he again measured the relative position of some of his stars and found fifty pairs where the position angle had changed by between 5 and 51 degrees. Thus began double star astrometry by which the masses of stars were to be determined in great number as time allowed the stars to revolve so much that an orbit could be calculated. The first orbit was obtained for the binary *Xi* Ursae Majoris by Felix Savary and published in 1827.

## 19th century: Finally parallaxes and meridian circles

Three men in the previous century, Rømer, Bradley, and Herschel, have been mentioned as motivated by the parallax question, but without the final success. Their efforts had however far-reaching consequences: The transit instrument and the meridian circle were invented; first-epoch positions were obtained in 1706 from which proper motions were derived in such number that the solar apex motion could be discovered in 1783; and double-star astrometry was begun in 1781 leading to the discovery of physical binaries and then orbits.

By 1840 parallaxes had been measured by three men, simultaneously and independently: Friedrich Bessel, Wilhelm Struve and Thomas Henderson, who had all been observing stars with large proper motions since that was now considered to be an indication of nearness. They published credible parallaxes for 61 Cygni, Vega, and α Centauri, respectively. John Herschel said: “It is the greatest and most glorious triumph which practical astronomy has ever witnessed”, speaking as President of the Royal Astronomical Society when he awarded the gold medal to Bessel. Bessel received the medal because he had shown the reality of the parallax most convincingly by his analysis.

The instruments used were respectively a heliometer, a wire micrometer, and a mural circle which had reached the necessary perfection through decades of technological developments, not least through a co-operation with the astronomer, who by his demands drove the technician to persevere with improving the instruments. The heliometer was originally developed in 1753 by London's John Dollond, the same man who had marketed the world's first achromatic refractors. Its purpose was to measure the diameter of the Sun, Helios in Greek, hence the name of the device. It was also called a “divided-lens micrometer” since the objective of the telescope was cut along a diameter into two semi-circles which could be positioned very accurately when they were shifted along the diameter. The observer would see two superposed images of the star field, one from each half, and he could shift the images, thus measuring separations of stars along the diameter. Bessel had used an outstanding example of a heliometer built by Joseph Fraunhofer in Munich. Struve used the largest refractor in the world, also from Fraunhofer. Henderson had only an ordinary mural circle, far less accurate; but his observations afforded a large parallax for α Cen of 0.91” which has later been reduced, and it is 0.742” from Hipparcos observations in our time.

This initial success spurred further activity, and results for the first dozens of parallaxes allowed some general conclusions to be drawn, e.g. that there is such a large diversity of luminosity among the stars that one can be millions of time brighter than another. But further progress was hampered by systematic errors, as could be seen when results from observations with different instruments by different observers were compared. Introduction of photography towards the end of the century did not bring a significant improvement to begin with, also because of systematic errors.

Measuring the distance to the Sun, needed to convert the stellar parallax measures into kilometres, renders an equally fascinating story as for the stars. Kepler wrote in 1620 that the distance must be at least three times larger than the antique (van Helden 1985). Ptolemy’s value was 1160 times the Earth’s radius. Kepler's value corresponds to a solar parallax of one minute of arc, i.e. the “horizontal parallax”, the angle subtended by the Earth radius as seen from the Sun. Publication by Flamsteed and Cassini in 1673 gave a value between 9.5 and 10”, based on observations from a favourable opposition of Mars in the year before. This is approximately correct as we now know, and implies a distance to the Sun 20 times larger than the antique value;

what a widening of the cosmos within a century! The following centuries brought a "struggle for the next decimal" by expensive expeditions to observe transits of Venus across the solar disc and by equally expensive observations of the minor planet Eros at opposition, as reported by Pannekoek (1961). The value was given in 1942 as 8.790" with a claimed accuracy of 0.001, and 30 years later 8.794,18" with an uncertainty of 0.000,05.

The new century began with a remarkable discovery by Guiseppe Piazzi of Palermo, who was using his alt-azimuth circle to assemble a star catalogue of greater accuracy than any of his predecessors. On New Year's Day 1801 he had measured a star that appeared to have changed its position when he measured again on a subsequent night. It turned out to be an object moving in an orbit between Mars and Jupiter, where a vast empty interval of distances from the Sun often had made astronomers wonder. By 1807 three more objects, Pallas, Juno, and Vesta, had been found in the belt of asteroids, as they were later called. By 1891, more than 300 asteroids had been found, and the pace of discovery then greatly increased with the application of photography.

Uranus and Ceres had been found quite unexpectedly during the study of stars. But in 1846 the large planet Neptune was discovered in an orbit beyond Uranus as a result of calculations based on many observed positions of Uranus. These positions deviated from the ones predicted by the mathematicians from Newton's law of gravity. J.C. Adams and U.J.J. Le Verrier were able to predict that an unknown planet could be responsible, and Neptune was found by J.G. Galle and H.L. d'Arrest in the predicted area of the sky on the first night. The discovery of Neptune was a spectacular and widely publicized victory of mathematical astronomy (e.g. Hoskin 1999).

Rømer's meridian circle of 1704 remained unique for a century during which mural circles were preferred for the measurement of star positions. But systematic differences between positions from different instruments of more than 10" were an increasing problem. The history of the meridian circle and how it became the preferred instrument by about 1820 has been studied by Herbst (1996) and Chapman (1990). The potential advantage of the full divided circle over the quarter circle had been realised by the astronomers, and the technical ability to manufacture and accurately divide the circle had come with the technical evolution. Achromatic objective lenses could now be made, but many technical issues played a role, and a rethinking of the astronomers took time. A transition period from 1780 to 1820 can be recognised; Piazzi's alt-azimuth of 1789, built in England, was the first instrument with a full circle, but it was in Germany that superlative meridian circles were first manufactured. It began with Repsold in 1802, then Reichenbach and Ertel, and now with full mechanical symmetry about the meridian plane which Rømer's instrument lacked. By 1820 continuous production of meridian circles was going on, and from 1850 the meridian circle had become the main instrument of an astronomical observatory.

Between 1859 and 1863, F.W. Argelander of Bonn, published a three-volume catalogue of 325,000 stars, known as the *Bonner Durchmusterung (BD)*, and a forty-plate atlas. It was the work of a tiny group of Bonn observers using a small refractor, and this survey was to prove immensely useful for observers for more than a century, but the positions were necessarily inaccurate. In 1867, therefore, Argelander proposed to the Astronomische Gesellschaft that a project be organized to measure, this time with great accuracy, the positions of the BD stars down to the ninth magnitude, and the work should be shared among observatories, each observing a zone of about five degrees in declination. The same idea had been expressed fifty years earlier by Bessel (1822), whose assistant Argelander had been at the time. The work started almost immediately, but proceeded slowly in some places, the last results appearing in 1910 for the northern declinations and in 1954 for the southern.

The slow progress with the meridian circles and the new photographic technique (the dry plate was invented in 1871) in 1885 led the director of the Paris Observatory, Admiral E.B. Mouchez, to suggest the possibility of a great photographic star chart, which became the *Astrographic Catalogue (AC)*. The long history of this great project includes the happy ending with a catalogue containing over 4.5 million star positions, published as AC 2000.2 by Urban et al. (2001) which was used as the major source of old positions to derive the proper motions of the 2.5 million stars in the Tycho-2 Catalogue.

## 20th century: Photography, radio astrometry, and a satellite

Photography was a very powerful astrometric technique during most of the 20th century, ending observationally about 1995 when photographic plates of the required quality were no longer manufactured. But the accumulated plates remain a valuable resource which is being exploited in catalogues with up to 1000 million stars. Combined also with CCD astrometry at new epochs, accurate proper motions are obtained. The idea of deriving absolute proper motions by differential, small-angle measures with respect to galaxies was proposed by Wright (1950) which lead to the NPM and SPM programs (Klemola et al. 1987). An account of the history up to 2008 of the observations and the resulting catalogues of positions and proper motions is given in Høg (2008b), including tables of selected catalogues. Present-day catalogues of astronomical and especially astrometric data are listed by Zacharias et al. (2004).

Meridian circles are able to measure large arcs on the sky and were therefore used to provide ever more accurate fundamental catalogues with positions and proper motions for about one thousand stars. Hertzsprung (1905) used proper motions from Auwers' Fundamental-Catalog (1879) as a measure of stellar distances, so-called secular parallaxes, when he discovered the dichotomy of red stars into giants and dwarfs; distances from trigonometric parallaxes were not accurate enough at the time.

Further reference stars were tied to the given fundamental catalogue by meridian circle observations, and by means of these stars the photographic plates could be reduced to a proper celestial reference system. Visual observation of the stars dominated meridian circle work during most of the century. It appears from Table 1 in Høg (2008b) that the error of a position in an observation catalogue improved from 0.9” in 1856 to 0.25” about 1910, and to 0.15” with the photoelectric observations in the Perth70 Catalogue (Høg & von der Heide 1976). The weight of this catalogue was ten times higher than that of Küstner's large catalogue of 1908, partly because Perth70 was observed in the many clear nights of Western Australia.

The CMC1-11 (1999) catalogues with the Carlsberg Meridian Circle on La Palma were observed with a photoelectric slit micrometer similar to the one used for Perth70, but with automatic control of micrometer and telescope, giving a much higher efficiency. Observed in the better seeing on La Palma and during 14 years instead of 5 years for Perth70 the weight of the catalogue is larger by a factor 30.

The accuracy of the CMC1-11 catalogues comes close to the limit set by atmospheric image motion for the measurement of large angles between stars, according to a formula by Høg (1968). Small angles can be measured much more accurately from the ground than large angles, according both to experience and to a formula by Lindegren (1980). The CCD astrometry, explained in Høg (2008b), gives better accuracy because the stars are referred to the dense set of reference stars in Tycho-2 within the small field of the CCD. The CMC14 catalogue was observed with CCDs, resulting in 0.034” accuracy from only two images of stars brighter than $13^{th}$ mag. Altogether, the catalogue weight is 500 times higher with CCDs on the same meridian circle on La Palma than with the slit micrometer, in spite of the shorter observing period.

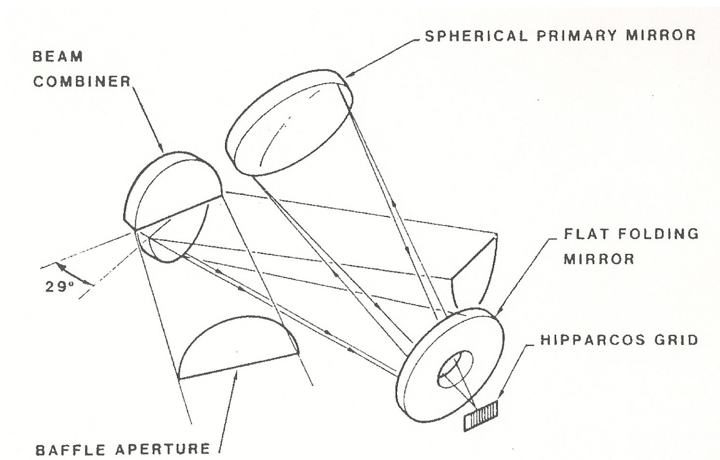


**Fig. 3** Hipparcos: Schmidt system with 29 cm diameter aperture, 1.4 m focal length and two viewing directions, all mirrors silver coated for maximum reflectivity. The satellite rotation makes the stars cross the modulating grid and the Tycho star mapper slits

Photoelectric techniques came to revolutionize astrometry with meridian circles, and even more with the Hipparcos satellite by ESA, observing in the years 1989-93. The evolution of photoelectric astrometry from the experiments by Bengt Strömgren in 1925 (cf. Fig. 2) to the Hipparcos satellite has recently been presented by Høg (2008a). The satellite is described in ESA (1997), the optical system is shown in Fig. 3, and results are summarized in Høg (2008b) and in the following section.

Radio astrometry with high precision was introduced in about 1970 by Ryle (1972) and others. It has since played an important role through observation of quasars because they are extragalactic and therefore have very small proper motions, if any, i.e. the quasars represent a non-rotating celestial coordinate frame. A non-rotating frame has traditionally, including the fundamental catalogue FK5, been established dynamically by the requirement that position observations of the Sun and planets must obey Newton's laws. Radio astrometry of the static frame of quasars is ideal for following the complicated rotational movements of the planet Earth. A selected set of 212 quasars defines the International Celestial Reference System (ICRS) to which the stars in the Hipparcos catalogue have been tied (Kovalevsky et al. 1997).

## Astrometry during 400 years

Errors of star positions and parallaxes in accurate catalogues are shown in Fig. 4. This means the *median external standard error* per star and coordinate in a catalogue*, if available*. In most catalogues the positions of bright stars are more accurate than those of faint ones. The representative median error, dominated by faint stars, is given for most catalogues.

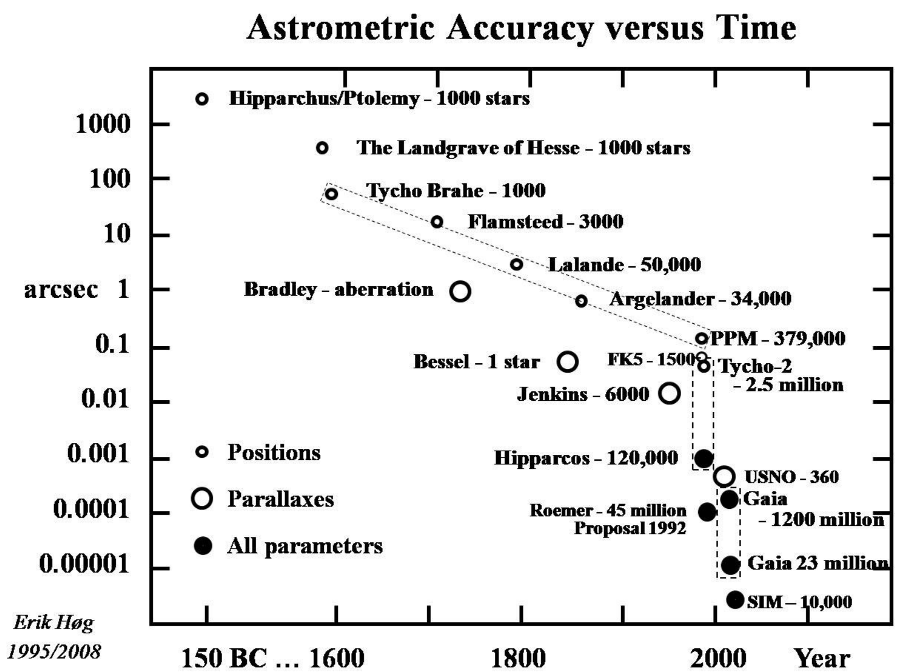


**Fig. 4** Astrometric accuracy during the past 2000 years. The accuracy was greatly improved shortly before 1600 by Tycho Brahe. The following 400 years brought even larger but much more gradual improvement before space techniques with the Hipparcos satellite started a new era of astrometry

It appears that the Landgrave of Hesse was able to measure positions with errors about six minutes of arc, ten times better than Hipparchus/Ptolemy in Antiquity. A few years after the Landgrave, and thanks to generous support from the king of Denmark, Frederik II, Tycho Brahe reduced the errors by a further factor of six. The Landgrave and Tycho, both wanted to equal Hipparchus by reaching the same number of 1000 stars. A period of 400 years followed with gradual improvement of the accuracy as astronomers always made use of the best technical possibilities of their time, especially with better time-keeping equipment and accurate manufacturing of mechanics, optics, and with electronics. The accuracy was improved by a factor of about 250 in 400 years, i.e. a factor four per century, and the number of stars was greatly increased.

The introduction of space techniques, however, with the Hipparcos mission (Perryman et al. 1997 and ESA 1997) gave a veritable jump in accuracy by a factor of 100 with respect to FK5, the most accurate ground-based catalogue ever. Hipparcos obtained a median accuracy of 0.001 arcsec for positions, annual proper motions and parallaxes of 120 thousand stars. The positions even in the Tycho-2 Catalogue with 2.5 million stars are as accurate as the positions in FK5 containing only 1500 bright stars. Tycho-2 includes proper motions, derived from Tycho-2 positions and more than 140 ground-based position catalogues, but no parallaxes. The median standard error for positions of all stars in Tycho-2 is 60 mas, and it is 7 mas for stars brighter than 9 mag. The median error of all proper motions is 2.5 mas/yr.

The points marked “parallaxes” might be labelled “small-angle astrometry” or “relative astrometry”, and all ground-based measurements of parallaxes are of that kind. This is about ten times more accurate than large-angle astrometry which was required to measure the positions shown in the diagram. The first such point is “Bradley – aberration” shown at 1.0 arcsec, the accuracy which Bradley obtained for the constant of aberration with his zenith sector. The accuracy of ground-based parallaxes begins with Bessel’s single star in 1838, followed by a factor 100 improvement in accuracy at the U.S. Naval Observatory in Flagstaff since about 1990 for faint stars.

“All parameters” means that about the same accuracy is obtained for annual proper motions, positions and parallaxes, as was in fact achieved with Hipparcos, for the first time in the history of astronomy. The Roemer proposal of 1992 (Høg 1993) introduced CCDs in integrating scanning mode in a space mission, instead of photoelectric detectors as in Hipparcos. Roemer promised a factor 10 better accuracy than Hipparcos for many more stars, and a development began which led to the Gaia mission due for launch in 2011. For Gaia an improvement by a factor of 100 over Hipparcos is predicted for the 23 million stars brighter than 14 mag, i.e. 10 microarcsec median error. The median accuracy is expected to be 180 microarcsec for the 1200 million stars in the Gaia catalogue brighter than 20 mag, much better than the accuracy of Hipparcos. The two dots for Gaia thus show the expected accuracy for bright and faint stars. Finally, in view of the expected Gaia results, studies are due about the scientific goals for ground-based optical astrometry after Gaia.

**Acknowledgements:** I am indebted to Adriaan Blaauw for the kind invitation to contribute to the symposium on this vast subject. Without the invitation I would never have engaged myself in this quite large undertaking. Comments to previous versions of the paper from F. Arenou, P. Brosche, A. Chapman, T. Corbin, D.W. Evans, C. Fabricius, F. Mignard, H. Pedersen, P.K. Seidelmann, C. Turon, S.E. Urban, W.F. van Altena, and N. Zacharias are gratefully acknowledged.

## References

Auwers A. 1879, Fundamental-Catalog für die Zonen-Beobactungen am nördlichen Himmel. Herausgegeben von A. Auwers. Publication der Astronomischen Gesellschaft XIV.

Boss B. 1937, Albany General Catalogue (GC) of 33342 stars.

Brosche P. & Schwan H. 2007, Der Zodiakalstern-Katalog von Zach und Barry aus den Jahre 1806, Mitteilungen Nr. 44 der Gauss-Gesellschaft e.V. Göttingen.

CMC1-11 1999, Carlsberg Meridian Catalogues La Palma 1-11, Copenhagen Univ. Obs., Royal Greenwich Obs., Real Inst. y Obs. de la Armada en San Fernando.

Chapman A. 1990, Dividing the circle: the development of critical angular measurement in astronomy 1500-1850. Contains extensive lists of references.

ESA 1997, The Hipparcos and Tycho Catalogues, ESA-SP-1200.

FK5 1988, Fifth Fundamental Catalogue, Veröff. Astron. Rechen-Institut Heidelberg, No. 32, by W. Fricke, H. Schwan, and T. Lederle.

Herbst K.-D. 1996, Die Entwicklung des Meridiankreises 1700-1850. GNT Verlag

Hertzsprung E. 1905, Zur Strahlung der Sterne (I), Zeitsch. für wiss. Photographie, S. 429-442. Reprinted in Ostwalds Klassiker der exakten Naturwissenschaften, Band 255.

Hoskin M. (ed.) 1999, The Cambridge concise history of astronomy.

Høg E. 1968, Refraction Anomalies: The mean power spectrum of star image motion. Zeitschrift für Astrophysik 69, 313.

Høg E. 1993, Astrometry and Photometry of 400 Million Stars Brighter than 18 Mag. Shanghai Sept. 15-19, 1992, IAU Symp. No. 156, 37.

Høg E. 2008a, Development of photoelectric astrometry including the Hipparcos mission. Proceedings of IAU Symposium No. 254 (in press), or at www.astro.ku.dk/~erik/History.pdf.

Høg E. 2008b, Selected Astrometric Catalogues, www.astro.ku.dk/~erik/AstrometricCats.pdf

Høg E. 2008c, Astrometric accuracy during the past 2000 years. www.astro.ku.dk/~erik/Accuracy.pdf

Høg E. & von der Heide J. 1976, Perth 70 – A catalogue of positions of 24,900 stars, Abhandlungen aus der Hamburger Sternwarte, vol. IX.

Høg E., Fabricius C., Makarov V.V., Urban S.E., Corbin T.E., Wycoff G.L., Bastian U., Schwekendiek P. & Wicenec A. 2000, The Tycho-2 Catalogue of the 2.5 Million Brightest Stars. Astron. Astrophys 355, L27-L30

Klemola, A.R., Jones, B.F., Hanson, R.B. 1987, AJ 94, 501.

Kovalevsky J. et al. 1997, The HIPPARCOS catalogue as a realisation of the extragalactic reference system. Astron. Astrophys. 323, 620

Lindegren L. 1980. Atmospheric limitations of narrow-field optical astrometry. Astron. Astrophys. 89, 41-47.

Lindegren, L., Madsen, S., Dravins, D. 2000, Astrometric radial velocities. II. Maximum-likelihood estimation of radial velocities in moving clusters. Astron. Astrophys. 356, 1119-1135.

Mignard F. & Froeschlé M. 2000, Global and local bias in the FK5 from the Hipparcos data, Astron. Astrophys. 354, 732.

Nielsen A.V. 1968, Ole Rømer and his Meridian Circle, in: Vistas Astr., Oxford Vol. 10, 105.

Pannekoek A. 1961, A History of Astronomy, London; translated from a Dutch book of 1951.

Perryman M.A.C. et al. 1997, The HIPPARCOS Catalogue. Astron. Astrophys. 323:L49-L52.

Ryle M. 1972, Nature 239, 435.

Urban S.E., Corbin T.E., Wycoff G.L., Makarov V.V., Høg E., Fabricius C. 2001, The AC 2000.2 Catalogue, Bull. Am. Astron. Soc., 33(4), 1494.

Wright, W.H. 1950, Proc. Am. Philos. Soc., 94, 1.

Van Helden A. 1985, Measuring the universe: Cosmic dimensions from Aristarchus to Halley. Chicago & London.

Zacharias, N., Gaume R., Dorland B., and Urban S.E. 2004, Catalog Information and Recommendations, at http://ad.usno.navy.mil/star/star_cats_rec.shtml