Astrometric Measurement Techniques

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Abstract

This contribution reviews the various principles which form the basis of astrometric measurements, such as meridian circle observations, imaging techniques, scanning satellites and interferometry. Various projects which employ those techniques are described, e.g. the Multichannel Astrometric Photometer, the Fine Guidance Sensors onboard the Hubble Space Telescope, the Hipparcos, Gaia and SIM Lite missions as well as the PRIMA instrument. This review covers both relative as well as absolute astrometric measurement techniques, from several milliarcsecond to microarcsecond precision.

Key words: astrometry, techniques, interferometry, space astrometry

1. Introduction

Astrometry is the oldest subfield not only of astronomy, but of all sciences in general. As a result, the techniques and objectives have changed considerably over time, which will be the focus of this review.

First of all, let us start with a definition. Astrometry deals with the measurement of the positions of objects on the sky, with ultra high precision and as a function of time. Furthermore, astrometry is also concerned with the modeling of the observed positions in terms of astrometric parameters like mean positions, proper motions and parallaxes as well as orbital parameters, if applicable. Last but not least, astrometry is also concerned with the establishment of a suitable coordinate system (or reference frame) for those positional measurements.

Astrometry forms the basis of astronomy. Without astrometry, and without stellar positional, proper motion and parallax catalogs, most endeavors in current astronomy would not be possible; those catalogs are an indispensable tool for modern astronomical research.

At first sight, the measurement of ever more precise positions might seem a bit boring. However, the scientific results which follow from pure positional measurements are just stunning: besides applications related to the kinematics, dynamics and structure of the Milky Way Galaxy and its constituents, one can, e.g., figure out the precise distances of objects and thus improve the cosmic

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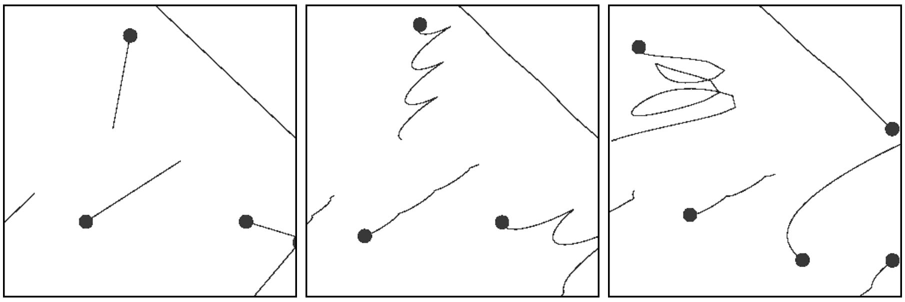

Figure 1: Paths of several stars as seen on the stellar sphere over time. The left panel only shows the linear motion of the stars on the sphere, which is called proper motion. The middle panel includes the offsets in the stellar positions introduced by parallax, so that an ellipsoidal motion with a period of 1 year is superimposed on the linear motion. Finally, the right panel shows the effect of proper motion, parallax as well as orbital motion (recognizable for some of the stars only).

distance ladder, one can identify the presence of extrasolar planets around other stars, and one can test the predictions of general relativity. There are even some less obvious applications related to e.g. earth climate studies; see Perryman (2008) for a comprehensive summary of scientific results based on the Hipparcos satellite mission (ESA, 1997).

A number of facts complicate the precise measurement of positions.

(1) First of all, everything on the sky moves, so that there is no single static reference point. Stars follow paths on the sky which can be described to first order by a linear motion (proper motion) plus the parallax ellipsoid; if the star has companions, any orbital motion around the center of mass of that system will be superimposed. The standard stellar model has five parameters (mean positions, proper motions, parallax), to which seven orbital elements have to be added in the case where the star has a companion, for a total of twelve parameters, and more if the star has more than one companion. An example of stellar paths on the sky, where the parallax and orbital motions have been exaggerated, is shown in Fig. 1. It is thus very difficult to define a coordinate system for the measurement of the positions.

Until the International Celestial Reference Frame (ICRF) was established, a number of fundamental stars have been used to provide the realization of a celestial reference system; the latest one was the FK5 system as given in the FK5 catalog (Fricke et al., 1988). The ICRF in contrast is defined by the positions of 212 quasars (Ma et al., 1998) and provides a quasi inertial reference frame, which coincides with the FK5 system to within the errors. Only quasars which show very little variation in their positions were chosen as defining sources for the reference frame. Since quasars are extragalactic objects with significant redshift, they are supposed to move very little, and their parallaxes should be below the measurement uncertainties and thus not recognizable. They show considerable radio emission, and are thus ideal objects for VLBI measurements defining the reference frame. One complication however one still has to deal with is variations in the structure of the source. The optical realization of the ICRF, the International Celestial Reference System (ICRS), is formed by a subset of stars in the Hipparcos Catalogue (ESA, 1997).

(2) Another complication for astrometric measurements is the fact that the body from which the observations are conducted (the Earth for ground-based observations or a satellite for space-based observations) is not a fixed point in space either. The Earth rotates about its own axis once each day, and superimposed on that are the variations in the orientation of the rotation axis itself, composed of precession, nutation and polar motion. The variation in the orientation of the rotation axis is only predictable to some extent; for the highest accuracy applications, one must rely on the measurements of the Earth orientation parameters, which are published regularly by the International Earth Rotation Service (IERS, `http://www.iers.org`). The precise knowledge about the orientation of the Earth rotation axis at the time of the astrometric observation must then be used to transform the astrometric observation into a coordinate system which is useful for the comparison of astrometric observations taken over a longer time interval, such as the barycentric coordinate system.

(3) The third complication in the precise measurement of positions on the celestial sphere is the fact that the motions of the objects are usually tiny. Proper motions of stars in our galaxy have values which range from several arcseconds per year for the most nearby stars to just a few milli-arcseconds per year for the more distant stars. The proper motion of other galaxies, or of individual stars in these galaxies, are on the microarcsecond level. Similar accuracies are required for parallax measurements: the largest parallax (for the primary component in the α Cen system) is 754.81 ± 4.11 mas in the new reduction of the Hipparcos data by van Leeuwen (2007). A star at 10 pc has a parallax of 100 mas, and a star at 100 pc has a parallax of 10 mas. All stars further away than 100 pc from the Sun have smaller parallaxes, so that one needs at least milliarcsecond precision for a 10% parallax at a distance of 100 pc, and much better than that for more distant stars. A milliarcsecond is a small angle though; at the distance of the moon, 1 mas corresponds to a linear size of just 1.9 cm. This makes it clear that we need clever measurement techniques, which are able to measure angles on the sky with extreme precision.

This review tries to give an overview of the most important measurement techniques and the way the various instruments deal with the difficulties in positional measurements described above. Section 2 describes the use of meridian circle instruments, as they were in use at nearly all major observatories for several centuries. Section 3 describes various imaging projects which perform relative astrometry in a single field, including astrometry with the Multichannel Astrometric Photometer and with the Hubble Space Telescope. Space astrometry with the Hipparcos and Gaia satellites is described in Section 4, while interferometry is covered in Section 5. Finally, a summary is provided in Section 6.

2. Meridian Circle Instruments

Meridian Circles (also known as Transit Circles) were the basic astrometric, if not astronomical, instrument for centuries (see e.g. Kovalevsky, 2002). All the major observatories had meridian circles in place, which were routinely used to measure the positions of relatively bright stars, and which were the basis of projects such as the Carte du Ciel (which finally resulted in the Astrographic Catalog, which is still heavily used today as first epoch for the calculation of proper motions) or the fundamental catalogs (FK3, FK4, FK5, the latter of which was compiled from 300 individual catalogs, and the General Catalog) which followed a bit later.

The measurement principle is the following (see Fig. 2): A star is observed during upper or lower culmination. The sidereal time during upper culmination is equal to the right ascension of the star, while the declination (or rather, the zenith distance) can be measured by adjusting the elevation of the telescope so that the star can be seen in the reticles of the telescope; encoders measure the tilt of the telescope in the vertical direction (elevation), which can then be converted to declination if the altitude of the observing site is known.

Since all stars culminate on the local meridian (which is the great circle passing through north and the celestial pole), that is in the same direction, the azimuth of the telescope is always fixed; the telescope needs to be able to rotate only around one axis (which is parallel to the horizon), so that different elevations can be reached.

3. Techniques for Relative Astrometry

3.1. Imaging Techniques

The imaging technique is the classical approach in particular for relative astrometry in a small patch on the sky. One just needs a single telescope and a detector, which could be either a photographic plate (in the past) or a CCD detector (today). Over the course of years, one would typically take several images per year of the same region on the sky and measure the position of a target in the frame of the surrounding (background) stars. Since very often the target is much closer than the rest of the reference stars in the field, the astrometric parameters such as proper motion or parallax are much larger for the target than for the reference stars. As a result, the relative values (the only ones which can be reliably measured with this technique) are close to the absolute ones and should be measurable.

Note that for this technique it is advantageous if the magnitude of the target star in the observed filter is not too different from the typical magnitude of the reference stars in the same filter, so that one can choose the integration time such that one gets a good signal-to-noise ratio for both target and reference. This means in practice that the method is very well suited for nearby but rather faint objects, such as late-type main-sequence stars or white dwarfs.

In the case of photographic plates, the positions of the stars are typically determined by a measurement machine in the local reference frame, i.e. relative

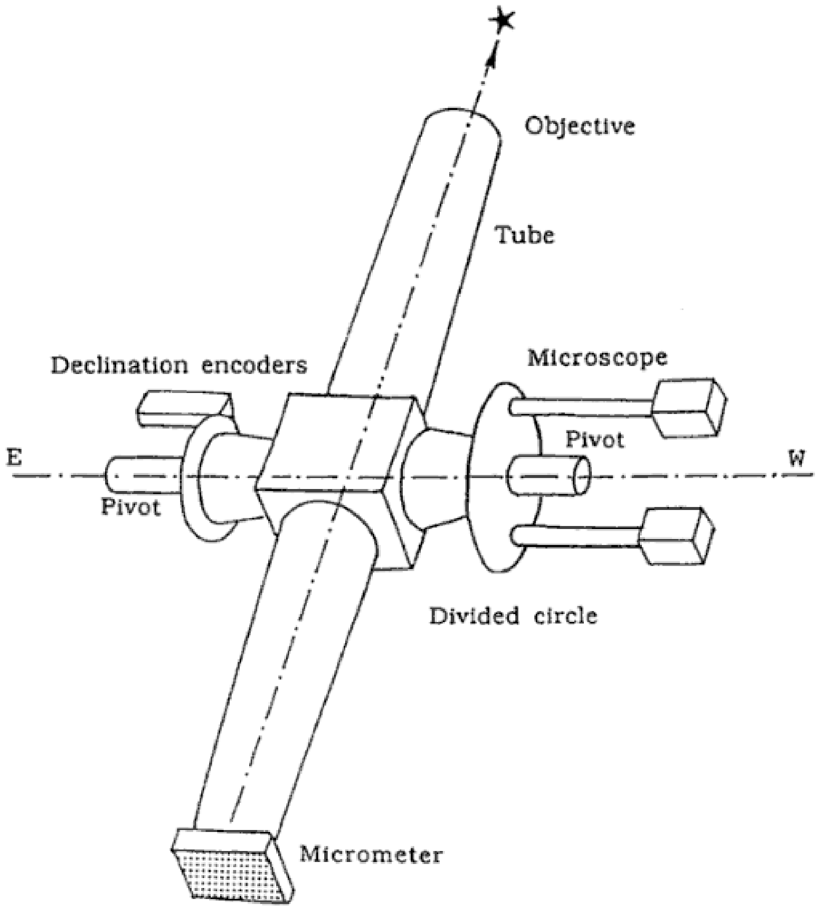

Figure 2: Schematic of a meridian circle instrument. The telescope is mounted on the local meridian, and the only movable axis is the one in east-west direction, used to measure the zenith distance. The right ascension is given by the sidereal time during the crossing of the local meridian. *This figure is reproduced with kind permission from the author and the publisher (Springer) from Kovalevsky (2002), Fig. 5.8.*

to each other. For the case of CCDs, the position of each star on the image is obtained via a centroiding algorithm, which could either be a simple PSF (point-spread-function) fitting or a more sophisticated approach such as has been described in Pravdo et al. (2005b), using Fourier transforms of the flux distribution in order to determine the precise centroids.

The astrometric accuracy with which the individual relative positions can be measured depends to a large amount on the plate scale (photographic plates) or the pixel scale (CCDs). If one assumes that centroiding is possible to 1/50 of a pixel, a pixel scale of about 400 mas/pixel (as applicable to the CTIO 0.9 m telescope) results in a centroiding accuracy of about 8 mas, while a pixel scale of about 61 mas/pixel (as applicable to the Palomar 5 m telescope) corresponds to a centroiding accuracy of only 1.2 mas for a single exposure.

Unfortunately, there is a competing requirement to a small pixel scale: a field of view as large as possible in order to have as many reference stars in the field as possible. The field of view at the CTIO 0.9 m telescope is about $8.6'$, whereas the field of view at the Palomar 5 m telescope is only $2'$, providing roughly a factor 18.5 fewer reference stars of the same magnitude compared to the larger field.

Another factor limiting the achievable astrometric accuracy with the imaging method is atmospheric image motion due to turbulence. The typical atmospheric noise is of the order of 1 mas, with a rather short correlation timescale of only 1 second. The limit of 1 mas can thus be overcome by taking many observations in a row and averaging the result. If the time in between observations is larger than 1 second, the astrometric accuracy will improve as the square root of the time over which the images are taken; hundred images taken at one epoch would get the atmospheric noise down to 0.1 mas. More details can be found in Pravdo & Shaklan (1996).

For relative astrometry, refraction itself is not a problem as long as all stars are affected by the same amount of refraction, which would not show up in the relative positions. However, this is not exactly the case since the amount of refraction depends on the color of the star. The residual refraction which is dependent on color is called differential chromatic refraction (DCR) and is an important correction step for relative astrometric data taken with the imaging technique. Its importance has been realized relatively recently only (see e.g. Monet et al., 1992), although it can often be the limiting factor for ground-based relative astrometry. For further details on the calibration of DCR for various projects, see Monet et al. (1992), Pravdo & Shaklan (1996), or Gubler & Tytler (1998) for a strategy which possibly calibrates DCR to a level of 10μas, provided that all necessary input parameters (such as temperatures of the stars) are known with the required accuracy. Alternatively, it is also possible to observe only very close to the meridian, where refraction is zero. A narrow-band filter would also reduce the amount of DCR, so that it is easier to calibrate.

Examples for on-going projects which implement the imaging technique for astrometry are the parallax program for nearby stars at CTIO (CTIOPI, see Subasavage et al., 2008, for the latest results), and the astrometric search for substellar companions to nearby stars (STEPS) by Pravdo et al. (2005a).

3.2. The Multichannel Astrometric Photometer

The Multichannel Astrometric Photometer (MAP), installed at the 30 inch Thaw Refractor of Allegheny Observatory, uses the grid modulation method to obtain rather accurate astrometric measurements. A very fine ruling is moved across the focal plane during observations, imprinting a modulation pattern on the stellar light. The intensity of the modulated light from various stars in the field is observed with photomultipliers behind a mask, and registered as a function of time (see Fig. 3). The relative phases of the modulated signals are directly related to the relative positions of the stars in field. One measurement only provides a 1-dimensional position; for the other direction, the ruling has to be moved in the perpendicular direction across the focal plane, and a second measurement of all field stars has to be taken. The measurement precision which was achieved with the MAP is of the order of a few milliarcseconds (Gatewood, 1987; Gatewood et al., 1993).

3.3. Astrometry with the Hubble Space Telescope

Astrometry with the Fine Guidance Sensors (FGS) onboard the Hubble Space Telescope (HST) also follows the principles of the imaging method, although no real images are being taken. The FGS were designed for milliarcsecond pointing stability of the telescope over extended periods of time. They consist of two orthogonal white-light interferometers each. Only two FGS are needed for pointing at all times, so that the third is free to be used for astrometry at the milliarcsecond level. At the heart of each interferometer is a Koesters prism, a device consisting of two prisms shaped like a triangle with a dielectric surface between them. The dielectric surface acts like a polarizing beam splitter: half of the incoming light is reflected, and the other half is transmitted with a 90° phase shift. The output intensity at each arm of the interferometer is registered by a photomultiplier. As a result of the properties of the Koesters prism, the output intensity is directly related to the angle between the incoming wavefront and the plane of the dielectric surface. The intensities at each arm of the interferometer are equal only if the wavefront entering the Koesters prism is parallel to its entrance surface. The signal S is defined as

$$S = \frac{PMT1 - PMT2}{PMT1 + PMT2} \quad , \tag{1}$$

where PMT1 and PMT2 are the output intensities of the two photomultipliers. The signal S is a function of the depointing angle, and resembles the shape of the letter S. This is the primary measurement of the HST FGS, and can be converted into positions on the sky. The measurements are performed such that while the guide interferometers point at two guide stars and keep the instrument stable, the third FGS points at 4 or 5 stars successively using field selectors which can rotate to various positions in the focal plane. The astrometry is relative with respect to the stars measured during one pointing. As with the other imaging techniques, the positions in both directions in the tangential plane are measured simultaneously. A number of corrections are required, such as

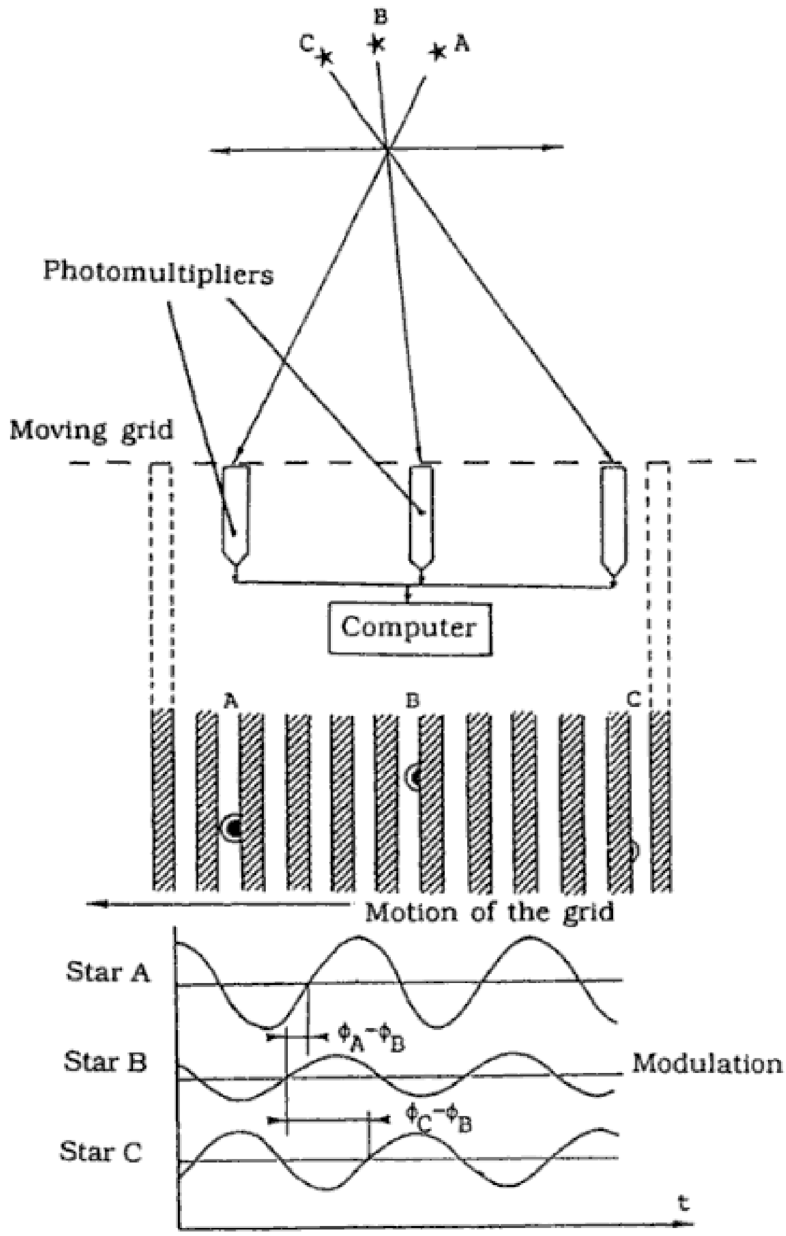

Figure 3: Illustration of the measurement principle of the Multichannel Astrometric Photometer. A grid is moved across the focal plane during the observations, resulting in modulation of the light intensity produced from the stars in the field which is observed with various photomultipliers. The phases of the modulated light intensity can be converted to 1-dimensional differential positions on the sky. *This figure is reproduced with kind permission from the author and the publisher (Springer) from Kovalevsky (2002), Fig. 6.3.*

for the not strictly simultaneous measurement of target and reference star, for differential aberration due to spacecraft velocity and the different locations of the objects in the field, and a chromatic correction due to small misalignments of refractive optical elements in the FGS (Duncombe et al., 1991). For recent results of HST astrometry, see e.g. Benedict et al. (2007) (Cepheid parallaxes) or Benedict et al. (2006) and Bean et al. (2007) (extrasolar planet masses).

4. Space Astrometry: Hipparcos and Gaia

4.1. Hipparcos

Around 1960, there was a need for more accurate parallaxes than could be obtained from the ground at that time. The scientific objectives were the calibration of the cosmic distance ladder and the interest in distances to certain kinds of objects which were not abundant in the immediate neighborhood of the Sun. With typical parallax accuracies of around 8 mas, a distance accurate to 10% or better could only be obtained for objects not further away than about 12.5 pc. The idea to go to space had been around for a while, but it was not immediately clear which strategy to pursue to reach the required astrometric precision.

In the late 1960's, the idea came up in France to observe two widely separated fields simultaneously (see e.g. Bacchus & Lacroute, 1974), which was later employed successfully on the Hipparcos Satellite (ESA, 1997). The advantage of observing two widely (58° in the case of Hipparcos) separated fields simultaneously in one focal plane allows very accurate measurements over large angles on the sky. By scanning the whole sky, all measurements can be related to each other, and the fact that the angles along a great circle add up to exactly 360° can be exploited. This measurement technique allows for absolute astrometry, and the measurements themselves can be used to establish a rather accurate reference system.

Going to space had several important advantages for astrometry: (1) The method described above, with two simultaneous fields of view, can only be implemented on a scanning spacecraft. (2) The whole sky is observable with a single instrument. (3) In space, there is no refraction, and no atmospheric image motion. (4) A much better thermal stability of the telescope can be achieved. (5) There are no distortions of the telescope structure due to gravitation. (6) The sky background is darker. (7) There is no bad weather which can get in the way of observations. So although in principle astrometric accuracies of the order of 1 mas can be achieved on the ground for individual observations (Connes, 1979; Lindegren, 1980), the measurement of the order of 100 000 parallaxes and proper motions over the whole sky, and the establishment of a corresponding reference system, would clearly not have been feasible from the ground.

Hipparcos was scanning the sky at a rate of $168.76''/\mathrm{s}$, completing one great circle in 128 minutes while maintaining a constant angle with respect to the Sun. The optical design of the satellite is shown in Figure 4. On the left, the beam combining flat aspheric mirror can be seen, which was cut in two

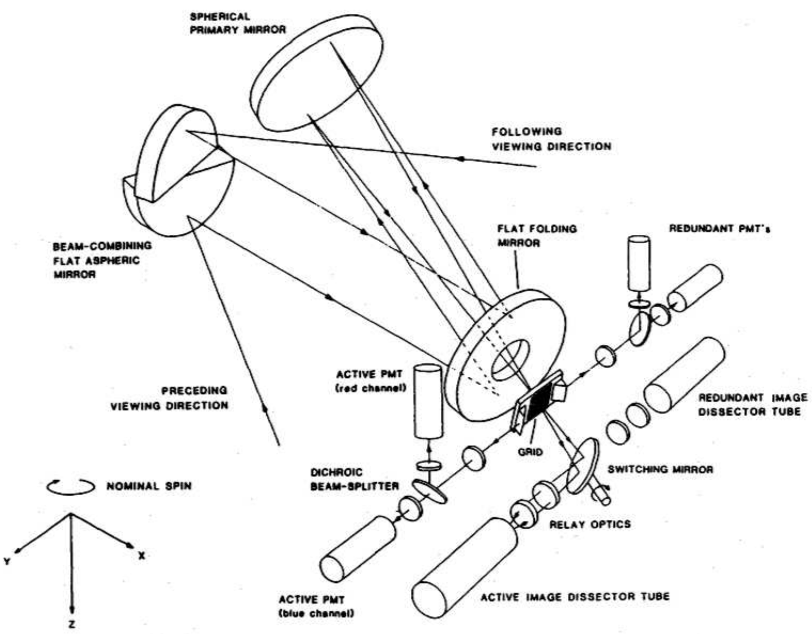

Figure 4: Illustration of the Hipparcos optics. The light from two widely separated fields hits the beam combining flat aspheric mirror and is reflected towards the same focal plane. A grid with very fine slits modulates the light as the satellite is scanning the sky. An image dissector tube observes the light pattern generated by one of the stars in the focal plane. Those observations are later combined into an absolute astrometric catalog of star positions, proper motions and parallaxes. *This figure is reproduced with kind permission from the author and the publisher (A&A) from Perryman et al. (1992), Fig. 1.*

halves and glued back together at half the basic angle so that light from two different viewing directions is reflected towards the flat folding mirror. In the focal plane, there is a highly regular grid with 2688 parallel slits which modulate the light intensity. The light pattern generated by the grid for one star at a time is registered by an image dissector tube. These photon counts as a function of time are the primary observable of Hipparcos; essentially, the astrometric measurement is thus a timing measurement since one measures the time at which a star passes through a certain slit in the focal plane and later relates this to an angular position on the sky. It is usually possible to assign slits to photon counts in a unique way, except in the case of binary stars which sometimes suffer from so-called grid step errors of multiples of $1.2074''$, which corresponds to the grid period.

The slits of the modulating grid provide a high accuracy astrometric measurement only in the direction perpendicular to the slits, which is the along-scan direction. The individual Hipparcos measurements are thus 1-dimensional only, and the second coordinate in the tangential plane could only be observed at another time when scanning the same field in a different orientation. These individual 1-dim measurements are called abscissae. Several tens of abscissae are usually obtained for each object; the precise number depends strongly on ecliptic latitude through the scanning law. In total, about 3 million abscissae were obtained for about 120 000 stars.

The data reduction of the raw Hipparcos data was - at that time - the largest data reduction task ever accomplished. Because of the measurement principle, all data were connected to each other, and a global iteration was required. The data reduction proceeded in three steps, the first of which was the great circle reduction, where the relative positions of all stars measured on a single great circle were determined. The next step was the sphere solution, where data from a larger number of great circles was combined and the zero-points of the relative positions on each great circle were determined. Finally, the astrometric catalog was produced by modeling all absolute positions of one star in terms of the five standard astrometric parameters (mean positions and proper motions in right ascension and declination and the parallax), or by including the appropriate orbital model in the case of binary stars. The final catalog contains data for 118 218 stars, with a median parallax precision of 0.97 mas (ESA, 1997). Note that the re-reduction of the raw Hipparcos data by van Leeuwen (2007) greatly reduced systematic errors in particular for the brighter stars, resulting in a much improved catalog.

4.2. Gaia

Gaia is based upon the same basic principle as the extremely successful Hipparcos mission, namely by observing the stars from two widely separated field in the same focal plane, scanning the whole sky and relating all measurements to each other, which results in a rather accurate, all-sky absolute astrometric catalog. The performance of Gaia however will be superior to the one of Hipparcos in many respects: the number of stars is increased to 1 billion (complete to about 20 mag in the visual), the astrometric accuracy will be of the order of about 10 microarcseconds, and in addition to the astrometry there will be spectrophotometry and radial velocities (down to a magnitude of about 16 in the visual). The launch is planned for no later than 2011.

In contrast to Hipparcos, Gaia will use a large array of CCDs for all of its measurements. They are operated in time-delayed integration (TDI) mode, where the scanning rate of the satellite is synchronized with the shift of the charge across the CCD columns until the accumulated charge is read out in the final column. Essentially, this is also a timing technique: the time is registered when the star passes the final columns of the CCDs. This time is later related to the direction into which the satellite was pointing at that time, so that the position of the star can be determined. For further information on the Gaia satellite, see ESA's website at `http://gaia.esa.int/`.

5. Interferometry

Interferometry is another way to accurately measure angles on the sky and perform astrometry. By combining light beams interferometrically, one converts the angular measurement on the sky into a linear measurement of the delay on the ground. Changing this delay by a fraction of a wavelength produces recognizable changes in the fringe pattern, so that the delay can accurately be adjusted for the measurement. Its linear size is then measured by a laser metrology system or similar.

Wide-angle absolute astrometry can be performed with interferometers simply by measuring the absolute delay which needs to be applied to one of the beams in order to obtain fringes. This internal delay then compensates the external delay which arises due to the position of a star on the sky; see Fig. 5. The unit direction vector $\vec{s}$ to the star can be figured out from

$$d = \vec{s} \cdot \vec{B} + C \quad , \tag{2}$$

where d is the delay, $\vec{B}$ is the baseline vector and C is the internal delay generated by the instrument. If the baseline vector and the internal delay are not variable in time to a good approximation, then their values can be fitted for by observing a sufficiently large sample of stars with known positions. Afterwards, the fits to the observed delays can be improved by allowing corrections to the absolute positions of the stars, thereby providing an absolute astrometric measurement. The Mark III interferometer (Shao et al., 1988; Hummel, 1994) as well as NPOI (Hutter et al., 1998) were operated based on these principles. The Mark III measurements achieved an astrometric precision of 20 mas in right ascension and 10 mas in declination (Hummel, 1994).

The PRIMA instrument (see e.g. Delplancke, 2008) will enable phase-referenced dual star interferometry at a relative astrometric accuracy of the order of 10 microarcseconds. The principle is sketched in Fig. 6: Two telescopes (in the case of PRIMA two 1.8 m Auxiliary Telescopes) are equipped with star separators, so that each of those telescopes can observe two stars (located at least $2''$, and ideally not more than $10''$ apart) simultaneously. The delay line is adjusted so

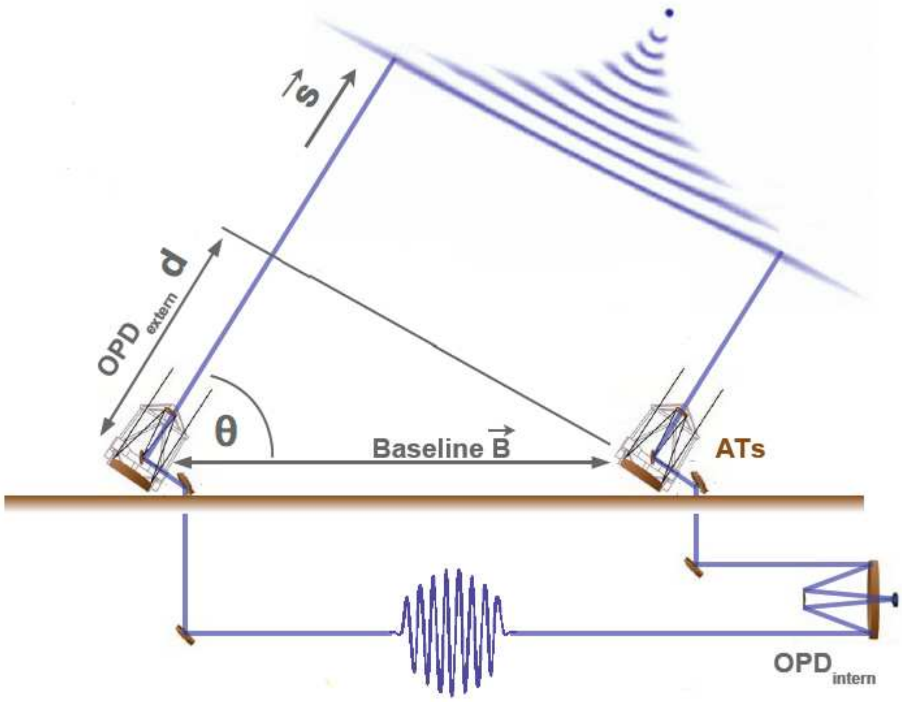

Figure 5: The principle of single star interferometry. A star is observed with two telescopes simultaneously. One of the beams is subject to an additional internal delay, which exactly compensates the external delay which arises because of the star's position on the sky (fringes are observed). If the baseline $\vec{B}$ and the internal delay are known, the unit direction vector to the star $\vec{s}$, projected onto the baseline, can be obtained from the measurement.

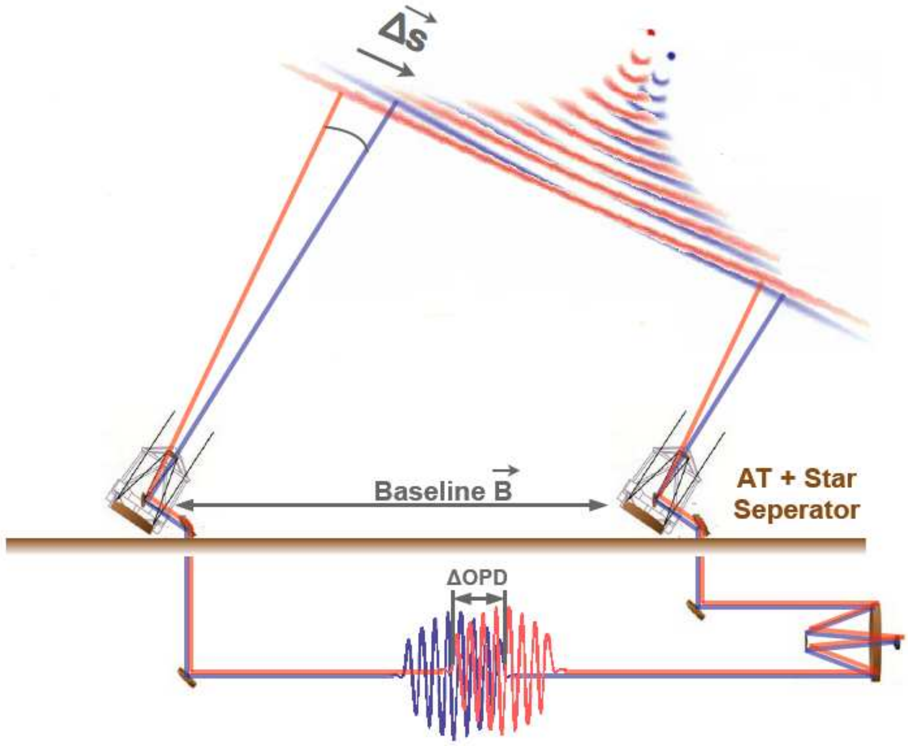

Figure 6: The measurement principle of phase-referenced dual star interferometry. Two stars are observed simultaneously with two telescopes, and the two light beams of each star are combined and the fringe pattern is observed. Both stars are subject to the internal delay as described for single star interferometry. In addition, the secondary star is also subject to an additional differential delay d, which is measured with laser metrology. The differential delay corresponds to the angular separation between the two stars $\Delta\vec{s}$, projected onto the baseline $\vec{B}$.

that fringes on the primary star are obtained. In addition, a differential delay is applied to the secondary star, and adjusted until fringes are obtained for the secondary star as well. In that case, the amount of differential delay Δd corresponds directly to the angular separation of the two stars $\Delta\vec{s}$ on the sky, projected onto the baseline:

$$\Delta d = \vec{\Delta s} \cdot \vec{B} + C \tag{3}$$

Again, the baseline $\vec{B}$ needs to be known. It can be obtained from the observations of stars whose positions are known at roughly the $0.1''$ level. As for the internal delay constant C, there is an easy way with PRIMA to obtain that number by switching the beams of primary and secondary star in the instrument. In that case, the difference between the differential delays in normal mode and in swapped mode equals two times the internal delay.

For closely spaced stars, but with distinct fringe packets, it is possible to do differential astrometry with a single beam interferometer. Muterspaugh et al. (2008) achieved an astrometric accuracy of 20 microarcseconds for bright close binary systems at the Palomar Testbed Interferometer.

Atmospheric effects are greatly reduced with the small star separation in narrow-angle astrometry, so that high relative astrometric accuracies can be obtained. As is in the case of the Hipparcos and Gaia satellites, one interferometric measurement provides only a one-dimensional measurement. In order to obtain the second dimension in the plane of the sky, one has to repeat the measurement with a different orientation of the projected baseline.

There are plans to take astrometric interferometry to space with the SIM Lite satellite mission (Goullioud et al., 2008), although the launch date is currently not clear. SIM Lite should provide absolute wide-angle astrometry at a level of 4.5 microarcseconds and relative narrow-angle astrometry at a level of 1 microarcseconds, which is clearly beyond current ground-based capabilities. A broad range of scientific topics can be tackled with that instrument; see Unwin et al. (2008) for a comprehensive review.

6. Summary

Astrometry is performed with one or with two telescopes, and from ground or from space. As a general rule, the highest accuracies are achieved with two telescopes and from space; the highest accuracy instrument currently in the planning is the SIM Lite mission, with a goal of 1 microarcsecond accuracy in narrow-angle mode. One further should distinguish between relative and absolute astrometry; examples for the former are most imaging techniques and their derivatives (see Sect. 3), while the classical example for absolute astrometry are the Hipparcos and the Gaia mission.

The methods with which astrometry are performed can furthermore be distinguished by the measurement principles. It is common to all methods that the measurement of a tiny angle on the sky is usually transformed into some other kind of measurement which is easier to carry out than an angle measurement (a principle which is applicable to the majority of all measuring instruments in physics). We can distinguish between timing methods such as the meridian circle instrument and the Hipparcos and Gaia satellites, imaging techniques, where the centroid of a pixel is measured on a CCD, the grid modulation techniques as employed by the Multichannel Astrometric Photometer and by Hipparcos (instead of an angle, the phases of intensities are measured), and finally the interferometric methods, where the resolution of a wavelength is used to make very exact linear measurements which can be converted into angles.

Finally, one often distinguishes between classical astrometry (e.g., with meridian circle instruments), and modern astrometry, which reaches milliarcsecond precision or better. The age of modern astrometry began with the Hipparcos satellite mission, which truly revolutionized the field of astrometry. Future missions such as Gaia and SIM Lite are expected to push those boundaries even further.

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