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ASTROMETRY WITH Gaia IN PERSPECTIVE

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Abstract. The astrometric accuracy of Gaia is placed in perspective by showing its expected performances in relation with the slow and unsteady historical progress, specifically in two areas: (i) the realisation of the reference frame, (ii) the measurement of trigonometric parallaxes. It appears clearly that both Hipparcos and Gaia are truly epoch-making steps in this age-old quest for accurate star position. No earlier generation of astrometrists has witnessed such a dramatic improvement over so short a period of time.

1 Introduction

With Gaia expected for a launch in less than four years, astrometry will benefit from a new decisive boost into the highest achievable accuracy, recurring just two decades after a similar outstanding landmark with Hipparcos. This will be the (provisionally) final result of a long quest that can be traced back to the origin of position astronomy.

As it stands today, Gaia is a powerful astronomical space project dedicated to high precision astrometry, photometry and spectroscopy. Starting in about 2012, Gaia will survey the whole sky and detect any sufficiently point-like sources brighter than the 20th magnitude with repeated observations over the 5-year mission. The astrometric precision of 25μas at 15 magnitude will improve on Hipparcos by nearly two orders of magnitude providing position, proper motions and parallaxes. These observations consist primarily of 1D accurate determination of the image location at the transit time on a frame rigidly attached to the payload together with an estimate of the source brightness. A global adjustment of these elementary observations produces the final astrometric solution with the five astrometric parameters for all the well-behaved stars. This rigid sphere is made inertial through the observations of distant, extragalactic, and non-moving quasars in the visible range.

For astrometry Gaia will be in 2020 the current best astrometric catalogue and the crowning of centuries of painstaking effort by generations of astronomers and instrumentalists to achieve the highest accuracy in pinpointing the stars. In this few pages I attempt to place Gaia in perspective by illustrating the major stages in the construction of reference frames and the measurement of stellar distances.

2 High precision astrometry

It is impossible to trace back the very moment when humankind started recording the position of heavenly bodies, and in the word *recording* we include organized oral transmission as a true mean to hand down a knowledge to posterity. It cannot be doubted however that the daily motion of the celestial sphere, the regular return of the sun in the morning were a shared knowledge within the small groups of humans. Very little is recorded before the apparition of true writing, although several megalithic monuments bear witness of the narrow relationship between the Neolithic man and the cosmos when distinction between science and myths or religion simply did not exist. Whatever the goal of these observations, the monuments can be viewed, at least partly, as astronomical observatories using long baselines to make accurate records of astronomical events from the alignments between markers. In short these early men were the forerunners of astrometry, that branch of astronomy dealing with the determination of the positions, distances and motions of celestial bodies.

This is one the oldest fields of scientific investigations, known for centuries as positional astronomy with social importance for astrology or timekeeping. Until the mid-19th century an astronomer was primarily a man

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able to describe the celestial sphere and its diurnal rotation to make predictions for the returns of the seasons, the planet wandering or the occurrence of eclipses. As positions and motions are not absolute concepts they can only be described with respect to some reference using a system of coordinates that can be constructed with much freedom.

Astrometry as it is understood today dates back at least to Hipparchus, who compiled in the 2nd century BC the first catalogue of stars visible to him and invented the stellar brightness scale basically still in use today. Hipparchus catalogue has come down to us through Ptolemy who published it in the 2nd century as part of his Almagest. (This sequence of events is, and by far, not shared by every historian, but seems to me very probable). This Hipparchus/Ptolemy Catalogue remained the standard star catalogue in the Western and Muslim worlds for over a thousand years, copied and updated by adding the effect of precession to the longitudes, until new observations by Ulugh Begh in Samarkand (early 15th century) and later by Tycho Brahe (late 16th century) led to the production of truly new catalogues of the stars accessible to the unaided eye.

Modern position astronomy, or in short astrometry, was founded by W.F. Bessel (see a short biography in Fricke, 1985) with his Fundamenta astronomiae, in which he gave the mean position of 3222 stars observed between 1750 and 1762 by James Bradley at Greenwich. Bessel is also credited and best remembered for the first real measurement of a stellar distance carried out on 61 Cyg in 1838, by which he opened up a totally new window on the scale of the Universe. Apart from the fundamental function of providing astronomers with a reference frame to relate their observations, astrometry is also fundamental for fields like celestial mechanics, stellar dynamics and galactic astronomy. In observational astronomy, astrometric techniques help identify stellar objects by their unique motions or predict the orbit of spacecrafts. Astrometry is also involved in creating the cosmic distance ladder because it is used to establish trigonometric reference distances for stars in the Milky Way, that is to say it sets the first rung of the ladder needed to determine the distances of the more distant sources belonging to the next rung. On a more mundane side, astrometry is still instrumental for keeping time, in that the UTC timescale used worldwide in science or for civilian activities is basically the atomic time synchronized to Earth's rotation by means of exact astrometric observations.

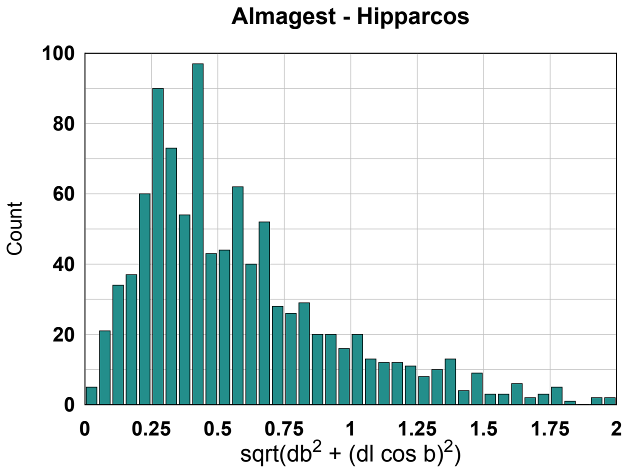


Fig. 1. Accuracy of the Almagest star catalogue (in degrees). The histogram is based on a comparison of the positionws provided by Ptolemy to those computed with the Hipparcos Catalogue. The date for the precession has been adjusted to give a zero mean in the residuals in longitude.

Since the early times star catalogues have never ceased to be used to chart the sky and to serve as reference maps to refer the motions of celestial bodies or the positions of fainter stars. As everywhere in science, refinements in the instruments and in computational techniques have been the main source of improvement of the astrometric accuracy from about one half of a degree at the time of Hipparchus to about $0''.05$ for the best ground based measurements of the early 1980s. The improvement in the realisation of the reference frame with fundamental catalogues is clearly visible in the list of Table 1.

Over the last two decades new astrometric techniques like radio interferometry on the ground or global astrometry in space in the visible has brought a considerable improvement with positional accuracy at the

$0\farcs001$ level. This enormous improvement in few years contrasts with the slow and steady progress which has been the rule for centuries and in the 20th century diverted young astronomers from starting a career in astrometry as they were lured by the nearly monthly breakthroughs in astrophysics.

3 Global space astrometry

The possibility to achieve global astrometry with a spinning satellite doing one dimensional measurements is not a trivial thing and has been the subject of animated discussions, and even challenged, before Hipparcos. The genesis from the initial proposal by P. Lacroute in 1967 to the Hipparcos selection is detailed in Turon & Arenou (2008) with first hand information. The principle which leads to absolute astrometry and nearly absolute parallaxes is still very subtle and deserves attention, all the more as it remains the Gaia baseline.

Table 1. List of the precision astrometry catalogues.

Year	Name	Number of stars	Comment
1790	Maskelyne	36	zodiacal stars, one epoch
1818	Bradley/Bessel	3000	no PM, nearly fundamental for one epoch
1830	Bessel	36	with PM, + precession
1878	FK1	539	Start of the FK series
1898	Newcomb	1297	Start of the GC series
1907	FK2	925	
1937	FK3	873	1st IAU supported international RF
1963	FK4	1535	$\sigma_{1950} \sim 0\farcs07$- $0\farcs15$, $\sigma_{2000} \sim 0\,\farcs15$-$0\farcs30$
1988	FK5	1535	$\sigma_{2000} \sim 0\farcs05$ - $0\farcs10$
1997	Hipparcos	100,000	Quasi fundamental catalogue
1998	ICRF	212(1)	First extragalactic primary reference frame

[1] This is the number of defining sources. The full ICRF has now more than 700 sources.

If one knows how the spacecraft rotates, meaning it rigid body attitude is available at any time, then from a local observation of point-source images onto the focal plane and a good time recording, it is clear that the position of each source can be recovered in the same reference frame in which the spacecraft attitude is given. Conversely with an on-board stellar catalogue and a star tracker rigidly connected to the spacecraft, one could know the attitude with great accuracy. In the case of Hipparcos or Gaia neither of the two is initially available (the Input Catalogue of Hipparcos was just a list of program stars, not an astrometric catalogue matching the observing accuracy). There is apparently a vicious loop since ultimately one wishes to determine the position of the stars and to know the spacecraft attitude. In practice this works thanks to the circle closure.

Consider the simpler case of a satellite rotating around a fixed spin axis and stars distributed on the perpendicular great circle, just in one dimension. After one revolution a star transits again in the telescope field of view, and between the two epochs one knows that the satellite has exactly rotated by 360 degrees (within a small amount related to the star proper motion). Since the time is recorded, one knows also the mean rotation rate averaged out over one revolution. But we have many stars at different longitudes on this circle, and each of them produces an average rate at a different time. One sees that it is therefore possible to reconstruct precisely the rotation of the satellite from purely geometrical and kinematical arguments. If one knows from a dynamical modeling that the rotation is smooth and that it can be modeled with few parameters, it becomes easy to fit these parameters. Within a single convention about the origin, one ends up also with the positions of the individual stars on the circle together with their proper motions. With Hipparcos and Gaia one has also the basic angle which tells us that a known rotation has taken place between an observation in the preceding and following field.

Finally the angular distance between pairs of stars will be quickly known if the star density is such that several stars are simultaneously measurable in both fields of view. Even in the simplified 1D celestial *circle* one sees that as soon as the number of arcs is large enough, there is only one way to place the stars, keeping at the end just one degree of freedom for the global rotation (or two if the stars have a proper motion).

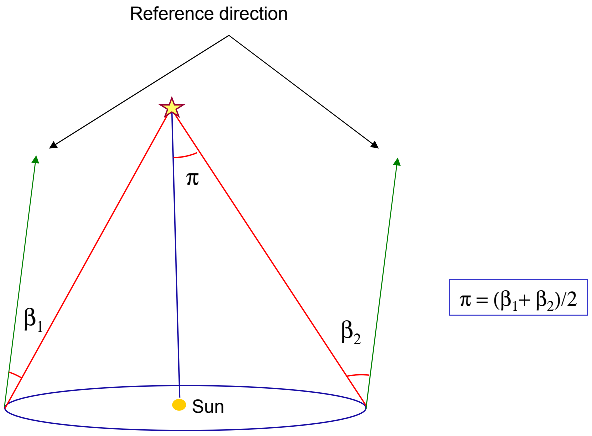


Fig. 2. Principle of measurement of absolute parallaxes. The star parallactic motion is monitored against an absolute reference frame or an absolute direction that can be accessed over the different observations. No other distant star is involved in the process and this should permit to obtain the true parallax of the star. This needs some form of global astrometry to maintain a consistent reference frame over the set of observations.

The same principle extends to the real celestial sphere, although there are several complications arising from the time change of the basic angle. Therefore the attitude reconstruction plays a very important and critical role in the reduction of a space astrometry mission aiming to carry out global astrometry. It is through the attitude reconstruction that the observations from the two fields of view become properly linked. It is therefore not helpful if one field of view contains many more stars than the other. To accommodate this for the Hipparcos mission, an Input Catalogue was created such that the stars were more or less evenly distributed over the sky. For Gaia a dedicated subset of stars will be used to solve for the attitude and the instrument parameters. Then the attitude solution will be used to find the astrometric parameters of the remaining stars.

4 Absolute and relative parallaxes

In many astronomy textbooks the principle of measuring stellar parallaxes is nicely presented, although there is little effort done to draw attention on the difference between relative and absolute parallaxes.

The parallactic effect is the difference in the direction of a distant celestial object as seen from two different viewpoints, that is to say the difference between two unit vectors. In classical astronomy the usual viewpoint was an observing place on the Earth, and the reference point was taken as the centre of the sun or, better, the barycentre of the solar system. Because of the annual motion, the parallactic vector is not constant during the year and the elliptical apparent displacement of the star cannot be incorporated into a linear proper motion. Quite naturally, one adopts as the standard direction of the star that defined in the barycentric frame. The annual parallax, usually referred to as the parallax, is the angle subtended at a star by one astronomical unit and is formally equivalent to the distance to the star. In principle a determination of this angle can be obtained by triangulation as illustrated in Fig. 2 which sketches the variation in the absolute direction of a nearby star. The possibility to do such a measurement implies that a reference direction can be materialised and transported in some way through the different observations while the Earth moves about the Sun. Given the size of the parallax, even for the nearest star, this is very hard to achieve. Typical measurements of this kind were carried out in the early days of the parallax search and later in the XIXth century successfully. The reference direction was either the local vertical (search of Bradley for example) or the spin axis of the Earth (measurement of stellar declination). This was the method used with success by T. Henderson at the Cape from which he determined

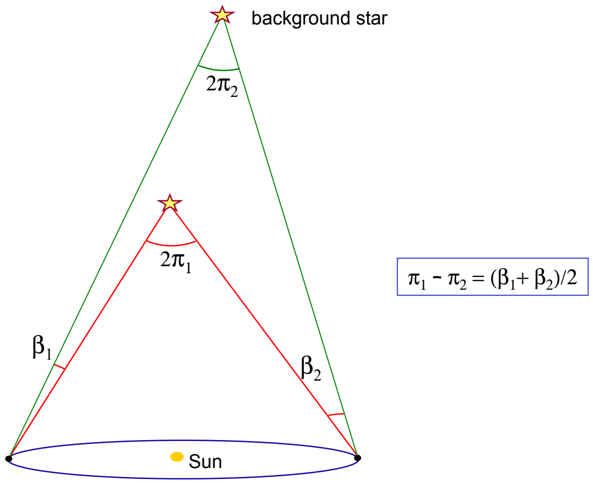


Fig. 3. Principle of measurements of relative parallaxes by referring the parallactic motion of a nearby star to a distant background star. This technique has been first described by Galileo in the Dialogo and considered as more promising than the absolute method. By nature it involves small field astrometry and requires an assumption about the distance of the background stars.

the parallax of α centauri in 1839 and later by others with meridian circles or zenithal telescope.

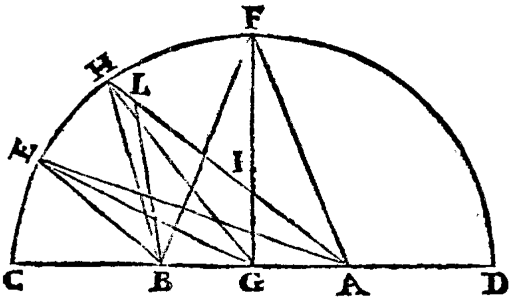
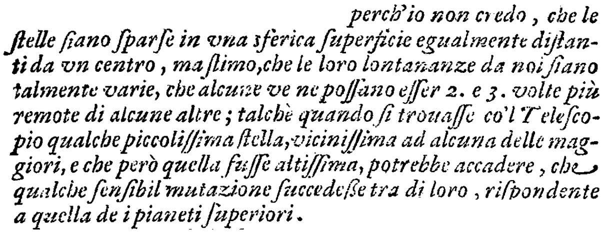


Fig. 4. Original drawing in the Dialogo (Third day) where Galileo describes the alteration in star elevation due to the motion of the Earth about the Sun. A and B are two points diametrically opposite on the ecliptic from where stars E, H or F (the latter at the ecliptic pole) are observed at six months interval. Galileo stresses that the change of directions should be visible in the direction of rising or setting of the star and that landscape features, like a remote hill, could be used as the arms of a gigantic quadrant.

In the Dialogues Galileo is probably the first to investigate rather deeply the consequences of the annual motion of the Earth on the position of the fixed stars. The qualitative features (i.e. the reflex stellar displacement) have been known for long, but Galileo set himself the objective of ascertaining the observable changes and how to actually do the measurements (Figs. 4- 5).

It took in practice more than 150 years between the first attempts to detect the parallactic motion and its undisputable first measurement by W.F. Bessel in 1838 on the star 61 Cygni. He was shortly followed in publication by F. Struve for Vega and T. Henderson in α Centauri. Work on measuring parallaxes proceeded very slowly with about 20 parallaxes available 10 years later and around 100 at the turn of the century. The number of known parallaxes varies greatly from one author to another since some quote the number found in the early compilation, while other attempt to tell how many *reliable* parallaxes are available at a particular time (Table 2). In the early days, for each star all the published parallaxes are listed and not necessarily discussed.



perch'io non credo, che le ſtelle ſiano ſparſe in vna sferica ſuperficie egualmente diſtanti da vn centro, ma ſtimo, che le loro lontananze da noi ſiano talmente varie, che alcune ve ne poſſano eſſer 2. e 3. volte più remote di alcune altre; talchè quando ſi trouaſſe co'l Teleſcopio qualche piccoliſſima ſtella, viciniſſima ad alcuna delle maggiori, e che però quella fuſſe altiſſima, potrebbe accadere, che qualche ſenſibil mutazione ſuccedeſſe tra di loro, riſpondente a quella de i pianeti ſuperiori.

Fig. 5. Original text in the Dialogo (Third day) where Galileo describes the relative parallaxes with reference to the geocentric motion of the planets. The text reads: *I do not believe that the stars are spread over a spherical surface at equal distances from one center; I suppose their distances from us to vary so much that some are 2 or 3 times as remote as the others. Thus if some tiny star were found by the telescope quite close to some of the larger ones, and if that one were therefore very remote it might happen that some sensible alteration would take place among them corresponding to those of the outer planets.* Translation of S. Drake, Univ. of California Press.

Several technics are involved with relative or absolute measurements and very often with scatter larger than the quoted individual precision, when available. In the modern era, the Catalogue entries are based on critical examination of the available values and lead to an adopted value with an estimated accuracy. For example the 4th General Catalogue of Trigonometric Parallaxes contains 15430 determinations of parallaxes for 7888 stars.

Table 2. Progress in the number of available stellar parallaxes.

Year	Number	Comment
1840	3	Published parallaxes
1850	20	Catalogue of Peters
1888	40	Catalogue of Oudemans
1910	100	of which 52 photog. parall. from Kateyn
1912	250	Catalogue of Bigourdan
1917	500	Catalogue of Walkey
1924	1870	Catalogue of Schlesinger
1930	2000	From here it may include spectroscopic parallaxes
1952	5800	Yale Parallax Catalog (Jenkins)
1965	7000	Yale Parallax Catalog (Jenkins)
1993	8000	Yale Parallax Catalog (van Altena et al.)
1997	110,000	Hipparcos

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