ABSOLUTE ASTROMETRY IN THE NEXT 50 YEARS - II

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RESUMEN

Favor de proporcionar un resumen en español. If you are unable to translate your abstract into Spanish, the editors will do it for you. With the Gaia astrometric satellite in orbit since December 2013 it is time to look at the future of fundamental astrometry and a time frame of 50 years is needed in this matter. A space mission with Gaia-like astrometric performance is required, but not necessarily a Gaia-like satellite. A dozen science issues for a Gaia successor mission in twenty years, with launch about 2035, are presented and in this context also other possibilities for absolute astrometry with milliarcsecond (mas) or sub-mas accuracies are discussed in my report at `http://arxiv.org/abs/1408.2190`. In brief, the two missions (2013 and 2035) would provide an astrometric foundation for all branches of astronomy from the solar system and stellar systems, including exo-planet systems with long periods, to compact galaxies, quasars and Dark Matter substructures by data which cannot be surpassed in the next 50 years.

ABSTRACT

With the Gaia astrometric satellite in orbit since December 2013 it is time to look at the future of fundamental astrometry and a time frame of 50 years is needed in this matter. A space mission with Gaia-like astrometric performance is required, but not necessarily a Gaia-like satellite. A dozen science issues for a Gaia successor mission in twenty years, with launch about 2035, are presented and in this context also other possibilities for absolute astrometry with milliarcsecond (mas) or sub-mas accuracies are discussed in my report at `http://arxiv.org/abs/1408.2190`. In brief, the two missions (2013 and 2035) would provide an astrometric foundation for all branches of astronomy from the solar system and stellar systems, including exo-planet systems with long periods, to compact galaxies, quasars and Dark Matter substructures by data which cannot be surpassed in the next 50 years.

Key Words: Astrometry and celestial mechanics — Planetary systems — Stars: distances, kinematics and dynamics — Galaxy: kinematics and dynamics

1. 2000 YEARS ASTROMETRY

Astrometry may be placed in three categories. *Absolute astrometry* ties observed positions of stars into a well defined celestial coordinate system. *Relative astrometry* is another important optical astrometric technique obtained with small-field telescopes, but is not included in the present discussion. *Radio astrometry* obtains absolute astrometry of quasars and other radio point sources by means of Very Long Baseline Interferometry, VLBI.

Absolute optical observations were mainly obtained by meridian circles located in both hemispheres in order to cover the entire sky. But this type of instrument became obsolete after the Hipparcos satellite mission launched by ESA in 1989. Three years gave absolute astrometry for a large number of stars. The main Hipparcos mission delivered absolute positions, parallaxes and annual proper motions for 120 000 stars with an accuracy of about 1 milliarcsec (mas) as never obtained before (Perryman et al. 1997). The Tycho star mapper experiment on board Hipparcos delivered accurate positions of the 2.5 million brightest stars in the sky published by Høg et al. (2000) in the Tycho-2 catalogue. Tycho-2 included proper motions derived from the satellite positions and the positions in 144 catalogues from ground-based observations during 100 years. Both catalogues are doing well: the number of citations in ADS are 1940 for Hipparcos and 1500 for Tycho-2.

The Hipparcos mission started a new era of astrometry which was continued by the Gaia mission launched by ESA in 2013. Gaia is two orders of magnitude more accurate in the five astrometric parameters and is surveying four orders of magnitude more stars than Hipparcos in a vast volume of the Milky Way. A combination of the Hipparcos/Tycho-2 catalogues with the first 14 months of Gaia observations was released in September (Brown et al. 2016) giving accurate positions for 1.1 billion stars and accurate parallaxes and improved proper mo-

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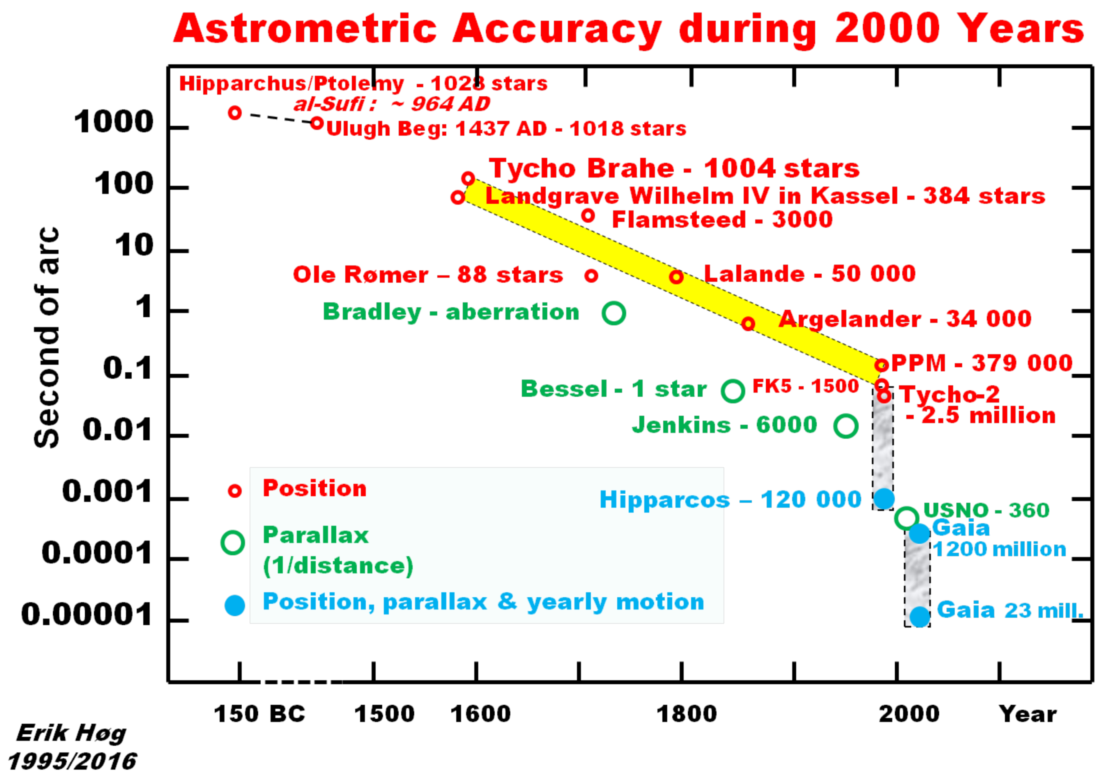

Fig. 1. Astrometric accuracy during 2000 years. The accuracy was greatly improved shortly before 1600 AD by the Landgrave in Kassel and by Tycho Brahe in Denmark (Høg 2016). The following 400 years brought even larger but much more gradual improvement before space techniques with the Hipparcos satellite started a new era of astrometry.

tions over a long 25 year baseline for 2 million stars. The final Gaia solution will establish a new optical reference frame by means of quasars, by linking the optical counterparts of radio (VLBI) sources defining the orientation of the reference frame, and by using the zero proper motion of quasars to determine a non-rotating frame (Lindegren et al. 2012).

The development of astrometric accuracy during two millenia is illustrated in Figure 1.

2. A GAIA SUCCESSOR IN 20 YEARS

With the Gaia astrometric satellite in orbit since December 2013 it is time to look at the future of fundamental astrometry and a time frame of 50 years is needed in this matter. The main issue is to build on the Gaia results of all-sky absolute astrometry for a billion stars. The Gaia successor (presently called Gaia2) should provide astrometry with equal or better accuracy for the same stars. It was proposed to ESA in May 2013 (Høg 2013). A common solution of the data from two missions 20 years apart will give proper motions with at least 10 times smaller errors and the parallaxes will be improved. Gaia2 would provide a new astrometric foundation for astrophysics, cf. Høg (2014), the science cases listed in Figure 2 and the following explanations.

Reference frame and imaging. The reference frame of a billion stars established by Gaia will be tied to quasars and the positions of individual stars will remain quite accurate over a long time: the errors at G=20 mag are predicted to be be 1.8 mas in 2026, 3.5 mas in 2036, and 8.8 mas in 2066. But a reference frame based on two missions will have 20 times smaller errors in 2066, 50 years from now.

This is an important improvement when optical imaging of radio sources with optical counterparts is considered, see Sections 3 and 4 in Høg (2014). The maintenance of astrometric reference frames in the long term is vital for the astrophysical analysis of high-resolution images obtained in different wavelengths. The high angular resolution of future large optical telescopes imposes requirement of a milliarcsecond or less on the accuracy. This can be satisfied by Gaia but only for some time. On a longer time scale a satisfactory reference frame can only be provided if a Gaia successor is launched in twenty years.

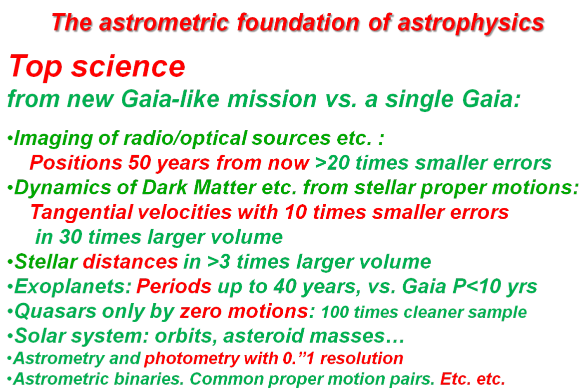

Fig. 2. A long-lasting astrometric foundation of astrophysics will be obtained by a new Gaia-like mission launched 20 years after the first. In addition equally fundamental photometric and spectroscopic data of high accuracy for the observed stars are collected by the astrometric satellites.

Proper motions for dynamics. Measurement of absolute parallaxes and proper motions by reference to distant compact galaxies with the E-ELT telescope is described in Section 4 of Høg (2014) and the accuracy is estimated; the ELT is now planned to have 39 m aperture and first light is expected in 2026. It is shown that a reference frame covering one half of the sky with many billion very faint stars could be produced from LSST observations and the Gaia catalog. The accuracies of such a frame would be about 1.0 mas for positions and parallaxes and 0.2 mas/yr for proper motions.

With 10 times smaller errors on proper motions and tangential velocities from two missions, the volume covered with a certain accuracy for a given type of stellar tracer becomes 30 times larger, and even more than that because the long-term proper motions are less affected by motion in binaries. The impact on the study of Galactic dynamics and dark matter is discussed in Section 2.5 of Høg (2014).

Astrometric Detection of quasars, i.e. solely from zero proper motion and parallax, unbiased by any assumptions on spectra, might lead to discovery of new kinds of extragalactic point sources. The incompleteness of quasar samples based on selection by optical photometry has been studied intensively for many years, see references in Heintz et al. (2015) and it is now well established that such samples miss a substantial number of in particular dust-reddened quasars.

Our strategy is to select quasar candidates solely on the basis of their lack of proper motion. This selection strategy also has the potential to select other extragalactic point sources, e.g. potentially new classes of objects. In order to examine the feasibility of this approach we needed to determine the number of false positives, e.g. how many stars will be selected in this way and where on the sky (or towards which galactic coordinates) will the problem of stellar contamination be most severe.

A catalog was used from the Gaia mission preparations to derive precise numbers for the expected true detections and for false detections due to stars which happen to show zero motion. We predicted that two missions would give 100 times fewer false detections than one mission because the proper motion errors will be 10 times smaller in both coordinates. This prediction has been confirmed by Heintz et al. (2015). For regions above 30 degrees latitude the ratio of QSOs to apparently stationary stars is above 50% and towards the poles about 80% when using Gaia data. With a Gaia successor in 20 years the ratio would improve dramatically at all latitudes.

Solar system studies. A report by Høg & Kaplan (2014) contains an overview, discussion and references based on correspondence with many experts and covering all aspects of the solar system where astrometry is important: orbits of planets, their moons, asteroids and NEOs, masses of asteroids, occultations of asteroids and KBOs (Kuiper Belt Objects), and families of asteroids and KBOs.

The roles of astrometry from the ground, from Gaia and from a Gaia successor are discussed. It appears that an accuracy of 1 mas from the ground can be reached for non-moving point sources, but it is expected that the same can be reached from the ground for solar system bodies from many nights of observations when phase effects are taken into account. It is expected that 0.1 mas will only be obtained with observations from space and that 1 mas will be possible from the ground.

A new reduction of old astrometric observations of solar system objects will be made when the Gaia reference star catalogue becomes available. This will give an increase in the accuracy of the many old observations obtained since photography was introduced about 1890. A Gaia successor will secure high-precision astrometry in the solar system also in the far future and it appears that a measurement accuracy of 1 mas will be sufficient because the irregularity of the figure of these objects will set a limit. But one expert claims that 0.1 mas would be useful.

Even if 1 mas is the limit, it appears that a Gaia successor is required to provide the reference stars since the Gaia frame will obtain large errors in the long run as listed above, e.g. 8.8 mas at G=20 mag

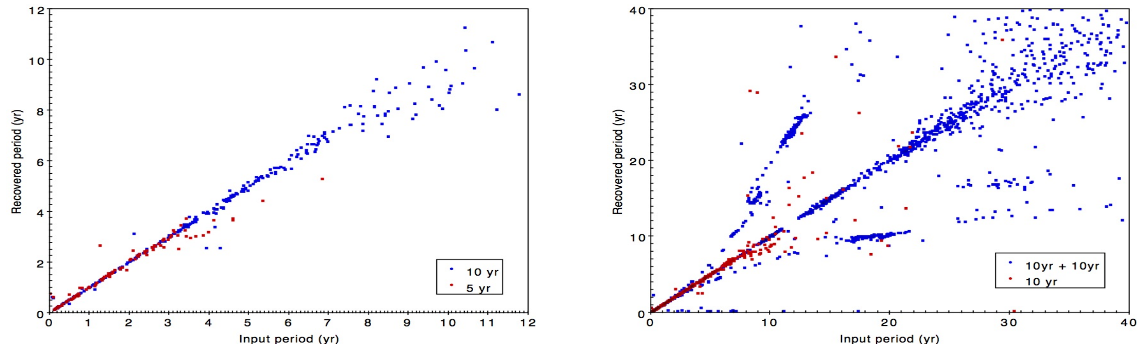

Fig. 3. The left figure shows the improvement in the possibility of detecting exoplanets with long periods and determining the periods when going from the nominal Gaia mission (5 years) to an extended mission (10 years). The nominal mission allows to detect some 20,000 planets with periods up to about 4 years while the extended mission shifts the limit to around 10 years. The right figure shows the improvement when adding a second 10 year mission with launch in 2035 to data from an extended Gaia mission (10 years). Planets with periods up to 30 years may be reliably detected. In some cases planets with periods up to 40 years may be detected, though with larger deviations on the periods (Images Ranalli et al., Lund Observatory, in preparation).

in 2066.

Exoplanets with long periods. The population of the outer parts of exoplanet systems is very poorly known, but this knowledge is required in order to estimate the effects of the migration inwards of outer planets through the habitable zone. The possibility of detections by astrometry is illustrated and explained in Figure 3.

Photometry with 0.1 arcsec resolution. Photometry of all stars at every field crossing is required for chromatic correction of astrometry and the photometry is used for astrophysical characterization of the stars. Gaia obtains photometry by low-dispersion prism spectra in blue and red, BP and RP, but these spectra have a length of 1 arcsec resulting in a confusion of photometry for double star components. This confusion is bad for both astrometric and astrophysical applications on double stars and stars in crowded fields. In Gaia2 therefore, filter photometry is proposed in 3 or 4 colour bands so that the high angular resolution of 0.1 arcsec is maintained. The prism photometry in Gaia serves this mission well in spite of the problems, but there is no strong reason to repeat the prism photometry after 20 years. A focal plane arrangement with 3 filters appears in Høg (2014) and with 4 filters, g'r'i'z', in Hobbs et al. (2016) where also the resulting accuracy is given.

3. GAIA SUCCESSOR WITH NIR CAPABILITY

An obvious technological improvement to the current Gaia mission is to go into the Near-Infra-Red (NIR). This would allow the new mission to probe through the Galactic dust to observe structure and kinematics of star forming regions in the disk, spiral arms and bulge region in order to obtain model independent distances and proper motions in these obscured parts of the sky. We have therefore submitted a proposal (Hobbs et al. 2016) to ESA for a study of a suitable detector with TDI, Time-Delayed Integration, as by the CCDs in Gaia. An answer from ESA is expected in December.

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