

ORBIT CHARACTERIZATION WITH HIPPARCOS AND GAIA

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Abstract. Combining absolute astrometry with direct imaging or radial velocities allows to better constrain the masses of binary systems. The absolute astrometry data from the Hipparcos (1990-1993) and Gaia (2014-) satellites allow us to use the long period of time between the two missions to accurately characterize orbits. Moreover, the exploitation of the Hipparcos data prepares us to use the future Gaia data in the study of binary systems. We will present here a new tool that combines the data from these two satellites rigorously, together with direct imaging and radial velocities. This modular tool can use the Transit Data from Hipparcos, which should be used in cases where the secondary light affects the observations. We will also present an example of its use with the case of GL494.

Keywords: binaries, astrometry

1 Introduction

The combination of multiple observational methods for the characterization of binary systems is frequently used because it allows to determine the masses in a system with the fewest assumptions.

The absolute astrometry method uses the evolution of the position of a star to retrieve the 5 astrometric parameters that describe it the best. These 5 astrometric parameters (AP) are the position (α and δ), the parallax (π) and the proper motion of the star (μ_α and μ_δ).

When the light from the secondary is negligible compared to the light from the primary star, what is called the photocentre (the centre of light of the system) is located on the primary star. This photocentre is moving, due to the presence of the secondary, around the barycentre of the system: this motion is called the reflex motion. When the reflex motion is detected in astrometry, the orbital parameters of the binary system can be determined: the period of the system, the periastron time, which is the date when the photocentre is closest to the star, the eccentricity of the system, the semi major axis of the orbit of the photocentre, the inclination of the system and two angles that orientate the system: the longitude of the ascending node and argument of the periastron.

All these parameters can be adjusted with our new tool, using a gradient descent method implementing automatic differentiation thanks to the R package: TMB (Kristensen et al. 2016). The absolute astrometry data used in the tool are presented in section 2, and the method for the combination of Hipparcos and Gaia data is presented in section 3. An example of a study done with this tool, GL494 system, is presented in the section 4.

2 Absolute astrometric data

2.1 Hipparcos data

The Hipparcos mission took place in the 90's and two data reductions are available: the original reduction (ESA 1997) and the new reduction (van Leeuwen 2007).

The observations from Hipparcos are given unidimensionnaly along great circles defined by each rotation of the satellites, and are denoted by $\Delta\nu$. These observations are in fact residuals between the real position of the star and the position of the star modelised with the astrometric parameters published in the Hipparcos catalog. The residuals $\Delta\nu$, the observational epoch and informations on the orientation of the great circle that path through a certain observed star are given in the Intermediate Astrometric Data (IAD, Martin et al. 1997 and van Leeuwen & Evans 1998).

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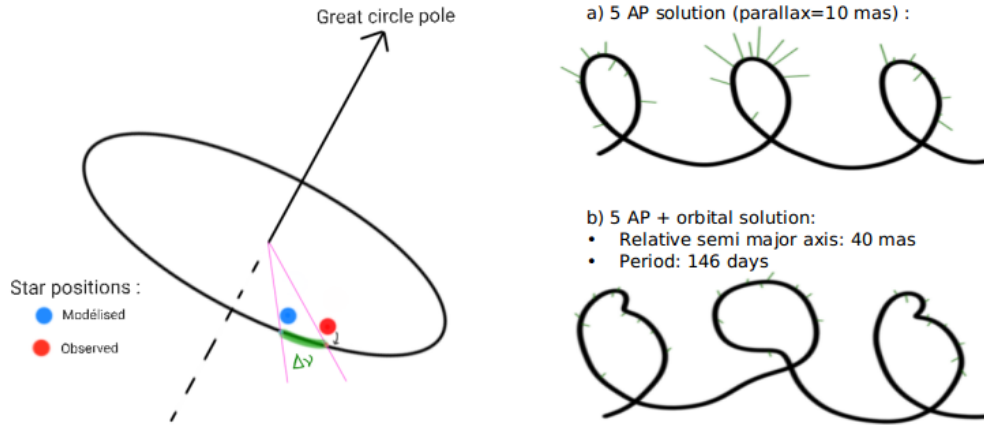


Fig. 1. Left: Projection on the great circle in green: residuals $\Delta\nu$. **Right:** Illustration of the astrometric solution, represented in black continuous line, and the residuals in green. **a:** 5 astrometric parameters solution. **b:** 5 astrometric parameters and orbital solution.

In the illustration in the right part of the figure 1 we plotted in green the residuals with significant size, but their orientation are chosen arbitrary. When comparing the size of the residuals between solution a and b we see that the residuals are minimized with the complete solution b*. It is important to notice that we have to be careful that the light of the secondary star does not affect Hipparcos detection in order to use the IAD. In Hipparcos, these systems where the secondary light impacts the data are listed in DMS-C (Double and Multiple System, with Component solution). In these cases, we can not use the IAD anymore and we have to use the Transit Data (TD, original reduction: Quist & Lindegren 1999 and new reduction: van Leeuwen 2007) from Hipparcos, that are also available in the reductions, and that contains additional light modulation informations. The other solutions from the DMS annex of Hipparcos are: G for acceleration solutions with 7 and 9 parameters, O for orbital solutions where the orbital parameters are estimated, V for the variability induced mover solution and X for stochastic solutions. All these solutions are described in ESA 1997.

An evaluation of the quality of the solution is also provided: the F2, which is a Gaussianized χ^2 . When this one is higher than 2, there is a potential signal that describes the reflex motion of the photocentre.

2.2 Gaia data

The Gaia mission (Gaia Collaboration et al. 2016b) started in 2014 and it is still ongoing. The different data releases (DR1: Gaia Collaboration et al. 2016a, DR2: Gaia Collaboration et al. 2018 and eDR3: Gaia Collaboration et al. 2021) provide the 5 astrometric parameters that best adjust the observations, without taking into account an eventual multiplicity: the multiplicity will be taken into account in the DR3 release.

The scanning law of Gaia, that gives for each star the epoch of observation and the angle of scan of the satellite is also provided for each release.

The RUWE (Renormalised Unit Weight Error) of Gaia evaluates the quality of the 5 AP for each star: if this value is higher than 1.4, then the published AP are not good and we have to check that the signal comes from an astrometric signal and not a flux contamination. The evidence of a contamination is a high rate of the *ipd_frac_multi_peak* flag in Gaia eDR3. The only solutions for considering the Gaia data of these stars is to wait for Gaia to solve the system, or wait for the Gaia's full data to be released (DR4). When it is the case, the tool uses the 5 AP of each components. It happens that the solution of one or both of the components is an astrometric solution with 2 parameters (the positional parameters α and δ): in these cases, the tool uses the 2 AP available.

*Because the observations are unidimensional, the real position of the star is located somewhere in a perpendicular line at the end of the lines that represents the residuals. This is not represented here for the purpose of simplification.

3 The combination of Hipparcos and Gaia data

The principle used by the tool is that it combines all the observations available (from direct imaging and radial velocity), together with the absolute astrometry from Hipparcos and Gaia, by adjusting the residuals from Hipparcos (from the IAD or the TD) and the 5 AP from Gaia latest reduction (eDR3 at this moment). If the star is resolved by Gaia, the 5 AP of the components A and B are adjusted as described in the section 2.2. The illustration of this principle is represented in the figure 2, with Hipparcos and Gaia in the same reference frame. The reference frame chosen in the tool is the Hipparcos frame.

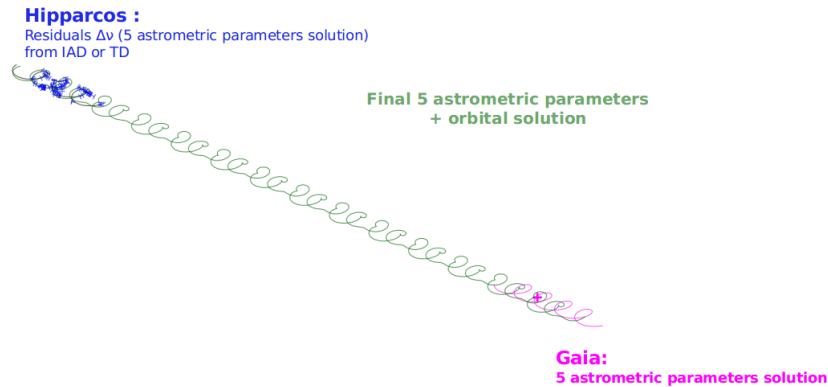


Fig. 2. Illustration of the principle of the combination of Hipparcos and Gaia data in the tool.

The principle of the Gaia’s frame rotation is to put the Gaia’s positions and proper motions in the Hipparcos proper motion reference frame as described in Lindegren et al. 2018, Brandt 2018 and Kervella et al. 2019. The errors on the positions, the proper motions and the parallaxes are also increased, and the difference between the zero parallax of Hipparcos and Gaia is taken into account. The values used for the rotation of Gaia eDR3 are given in Fabricius et al. 2021.

The method consists then in the adjustment of a 5 AP solution with the Hipparcos epoch as reference. This solution is then propagated at the Gaia epoch while taking into account the radial velocity of the source: the new solution is then called the AP_G . The Gaia AP published cannot be compared with the propagated solution AP_G , because in the Gaia AP, the 5 AP tries to describe a more complex motion: the one of the barycentre and an additional reflex motion. However, since we are adjusting the orbital solution, we can predict where the two companions are at the time Gaia observed. Thanks to the epochs of observations and the orientation of the satellite provided in the scanning law, we can simulate Gaia’s residuals corresponding to the reflex motion, and then deduce the 5 AP solution that would have been observed by Gaia and compared it with the Gaia AP published through a χ^2 using a covariance matrix.

4 Example case: GL494

This star is a variable star studied in direct imaging by Bowler et al. (2020) and in radial velocity by Tal-Or et al. (2019). The relative orbit is well covered with 16 observations, and an estimation of the magnitude difference in K band is also provided: $\Delta m_K = 4.27 \pm 0.02$. The 65 observations available in radial velocity are very impacted by the stellar variability.

For this system, the magnitude difference between the two stars is significant so the light of the secondary star is negligible. Gaia does not resolve the system and the RUWE value is 4.19: the signal contained in Gaia is due to the reflex motion of the primary star, so we can use the 5 AP published. There is also a proper motion anomaly detected by Kervella et al. (2019), a solution type in the Original Reduction of Hipparcos that detected an acceleration (7 parameters solution), and an F2 with a value of 2.32 in the New Reduction of Hipparcos, that indicates that the simple 5 AP solution is not sufficient and that there is a reflex motion signal.

Here is represented the adjustment of the direct imaging data with the IAD from Hipparcos and Gaia’s 5 AP solution from eDR3. The radial velocity data are not used because of the variability but we will check their agreement with the adjustment after.

The parameters determined with this new adjustment are compatible with the parameters published by Bowler et al. (2020). This adjustment is represented in the figure 3 together with the observations. For Hipparcos, the new residuals are represented.

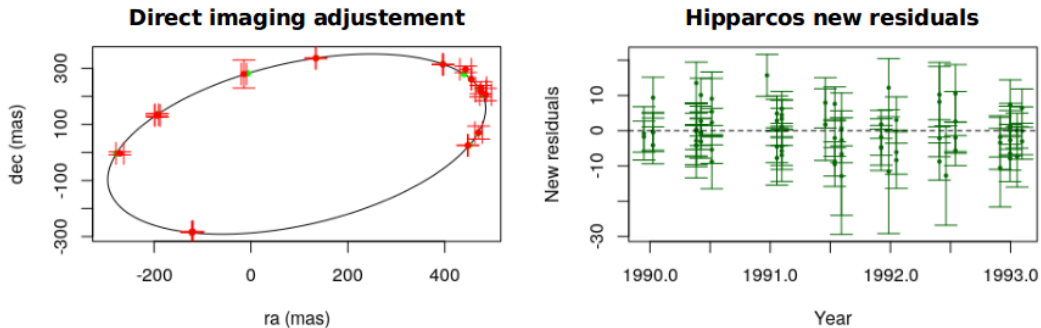


Fig. 3. Left: Direct imaging adjustment: The observations are represented in red, the relative orbit from the adjustment is the continuous line in black and the real epoch of observations are the green dots. **Right:** The new Hipparcos residuals are represented in green. They are the residuals from the new 5 AP determined from the adjustment.

The observations in radial velocity are also in good agreement with the adjustment from the relative and absolute astrometry data, and the variability is responsible of the noise around the adjustment. Finally, what is new here is the estimation of the individual masses of the system, that will be published soon.

5 Conclusion

Here we have introduced our new tool that combines the available absolute astrometric data from Hipparcos and Gaia together with complementary observations such as radial velocity and relative astrometric data. For now, the tool have been tested on several stars as well as on simulated data and it allows us to identify the advantages and disadvantages of it. The first advantage is obviously that it is a realistic approach that adjust all the observations available together, and the second is that it is the closest method that will be used with the future Gaia full data. The disadvantage is that this method work only on well-constrained orbit, and so, it need enough data. The expertise on the Transit Data offers to study also resolved stars by Gaia, and this topic will be a part of an upcoming article, together with the presentation of the tool, and the study of several interesting stars such as GL494.

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