Double Stars and Astrometric Uncertainties in Gaia DR1

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Abstract

A significant number of double stars with separations up to 2.5 arcsec are present in the Gaia Data Release 1 astrometric catalogs. Limiting our analysis to a well-studied sample of 1124 doubles resolved by Hipparcos, provided with individual Tycho component photometry and cross-matched with the TGAS catalog, we estimate a rate of at least 3% for brighter double stars in Gaia DR1, which should be resolved in future data releases. Gaia astrometric results are affected by unresolved duplicity. The variance-normalized quadratic differences of proper motion between Gaia and Hipparcos do not follow the expected χ² distribution and show signs of powerful degradation in the components aligned with the axes of the double systems. This concerns only pairs with separation below 1.2–1.5 arcsec, which mostly remain unresolved in Gaia DR1. On the other hand, the orthogonal proper motion components and parallaxes do not have any detectable perturbation, as well as all astrometry for separations above 1.5 arcsec. Gaia parallaxes do not seem to be perturbed by duplicity, with Gaia–Hipparcos differences being systematically smaller than the expectation. The rate of incorrectly identified, or swapped, companions is estimated at 0.4%.

Key words: astrometry – binaries: visual – parallaxes – proper motions

1. Introduction

The first release of the Gaia mission data (Gaia DR1) includes accurate positions, parallaxes, and proper motions for more than 2 million Tycho-2 and Hipparcos stars and positions only for the larger Gaia sample of 1.1 billion objects (Brown & Gaia Collaboration 2016). The former part, called TGAS, was constructed differently from the large catalog (Lindegren et al. 2016). The proper motions of TGAS stars in DR1 were computed using Hipparcos and Tycho-2 positions at, or close to, the epoch J1991.25, and Gaia’s own position determinations around J2015. Thus, the TGAS astrometric solution is only partially independent of the previous Hipparcos and Tycho-2 catalogs. However, Gaia DR1 proper motions and parallaxes are presumed to be practically independent of their counterparts in the Hipparcos catalog because the latter were not explicitly used in the astrometric reductions. A conscious effort was made at the catalog production stage to improve the reliability of DR1 astrometry in TGAS (at the expense of completeness) by filtering out all sources with standard formal errors of parallax in excess of 1 mas or 20 mas in positions, per coordinate. It is important to note, in the context of this Letter, that this filtering was not meant to discard specifically blended double sources or other perturbed images because the formal errors are not sensitive to the observed scatter of residuals. As explained by Fabricius et al. (2016), some double star and optical pair components could be removed as parts of duplicated entries mostly originating from redundant entries in the Initial Gaia Source List. The threshold near-neighbor distance for this additional filtering (typically, 59 mas) was lower than the separation of double stars resolved by Hipparcos and Tycho. Therefore, it is not surprising that some known double stars with separations below 2.5 arcsec survived this filtering and were included in the DR1 and, sometimes, with both components as separate entries.

The goal of this Letter is to estimate the frequency of unresolved double stars in Gaia DR1 catalogs using a well-defined and reliable sample of pairs previously resolved by Hipparcos and Tycho and to investigate the expected astrometric degradation caused by unresolved duplicity. A similar validation effort is briefly discussed by Arenou et al. (2017). They note occasional gross errors in astrometry and photometry resulting from Gaia sources being cross-identified with the wrong components of resolved pairs. Here, we compare Gaia DR1 data with the original edition of the Hipparcos catalog (ESA 1997) because the later re-processing by van Leeuwen (2007), which was used by Arenou et al. (2017), contains strongly underestimated standard errors for brighter stars (Frouard et al. 2015; Arenou et al. 2017). This inflates the χ² statistics of astrometric differences in an external comparison and hides the additional perturbation caused by duplicity.

2. The Sample

We start with the relatively well-studied collection of 9473 components of double and multiple systems resolved by Hipparcos and listed in Fabricius & Makarov (2000). The Double and Multiple Systems Annex (DMSA) of the main Hipparcos catalog lists over 12,000 double and multiple systems with separations between 0.1 and 2.5 arcsec. More than 10% of Hipparcos stars were resolved with these separations. The special photometric solution for these systems, which was a derivative of the Tycho-2 project (Høg et al. 2000a, 2000b), produced separate BT and VT magnitudes (similar to Johnson B, V; see Bessell 2000) for components of more than 7000 systems, but only 5173 systems with separations greater than 0.3 arcsec were ever published. We choose this well-defined and reliable sample over the larger DMSA collection because the latter contains a fraction of low-

A small correlation of Hipparcos and Gaia proper motions may still be present because of the nonzero covariances of positions and proper motions in each catalog.
quality and suspicious solutions at smaller angular separations and because the additional color information allows one to estimate more subtle photocenter effects for unresolved doubles.

Each of the 9473 components in the initial sample was cross-matched with TGAS using HIP identification numbers. The number of components found in TGAS is 2768. Thus, approximately 29% of the resolved double and multiple systems with separations between 0.3 and 2.5 are present in TGAS. Using the rate of resolved doubles in Hipparcos and this estimate, we should expect roughly 3% double or multiple stars to be present in Gaia DR1 at brighter magnitudes (G <= 13). At fainter magnitudes, the rate of optical pairs goes up and field confusion becomes a significant factor. Since the DR1 pipeline was not set up to specially treat close double images, a significant fraction of the astrometric catalog may be impacted.

Only one TGAS entry was found for each cross-matched double in the sample. This implies that DMSA systems having the same HIP number are never resolved in TGAS. In most cases, the matched TGAS entry corresponds to the brighter component, but sometimes the magnitudes are close and the wrong component is identified in TGAS. The secondary Gaia DR1 catalog (with positions only) does include sources matching some of the secondary components. By inspecting a random sample, we found that most of the doubles with separation above 1.5 were resolved in the secondary catalog, while most of those with smaller separations were not. Thus, an effective threshold resolution of the Gaia DR1 catalog is about 1.5 at brighter magnitudes, although much closer pairs are sometimes resolved into separate entries too. The separation limit may be higher for the fainter general DR1 stars. For a discussion of the general angular resolution of Gaia DR1, see also Section 4.4 and Figure 17 of Arenou et al. (2017). In the following, we will concentrate on the 2768 cross-matched TGAS components in an attempt to detect the impact of duplicity on the astrometric performance.

As an intermediary verification step, we can use the TGAS parallaxes (far superior to Hipparcos parallaxes), Hipparcos Hp magnitudes, and the Tycho-2 BT and VT magnitudes for individual components to construct an improved HR diagram. Figure 1 shows a diagram for 838 pairs with statistically significant parallaxes of primaries, \( \zeta / \sigma > 7 \). The primary (A) components are marked with open circles and the secondaries with red dots. The parallax of a secondary is always assumed to be equal to the parallax of the primary found in TGAS. This is correct for physical binaries but is wrong for optical pairs, which should be dispersed across the diagram. Indeed, as the primaries show a well-defined main sequence, red clump, and a giant branch, the secondaries seem to be more dispersed around the main sequence. Some of the deviant secondaries may be optical pairs, others may reflect occasional gross errors in the BT, VT magnitudes. Note that several supergiants are present among the primaries and a few possible hot subdwarfs (sdB) among the secondaries. Some of these special cases deserve a separate study, but the general

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Figure 1. HR diagram of 1676 components of double stars with Tycho BV magnitudes and Gaia DR1 parallaxes. Primary components are shown with open circles, secondary with red dots.

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4 In fact, each unique HIP number appears only once in TGAS.
conclusion is that most of the systems in the sample are physical binaries and the quality of Tycho photometry and Gaia astrometry is high. This result also confirms that the majority of resolved double systems are matched with correct TGAS sources.

Some of the DMSA systems are represented with only one component in the Tycho-2 sample. Such lonely components were included when the secondary was too faint for a confident detection in the Tycho observations, i.e., when the signal-to-noise ratio was below a threshold level. The number of complete Tycho pairs in the set matched with TGAS is 1124, but many of them have not been resolved by Gaia. What are the separations of these pairs? Figure 2 shows the distribution of these doubles in the $\Delta H_p$ magnitude versus separation plane. Surprisingly, we do not see a pronounced bias of the doubles with at least one matching entry in Gaia DR1 toward larger $\Delta$mag or smaller separation, although a small pile-up is present in the lower right corner of the graph. This confirms that the decision whether to include a star in Gaia DR1 was not directly related to the shape of the image. On the other hand, pairs with a small magnitude difference may have a better chance to make it to the release because they need the same exposure time (or gate setting). Perhaps, the “significance of excess noise” parameter $D$ given in TGAS should be more informative about the degree of perturbations observed for a given object. If $D > 2$, the amount of extra noise is statistically significant, and only a few percent of regular, unperturbed stars are expected to have it. The range of $D$ is between 10 and 13000 for our sample, indicating a high degree of perturbation and extra noise. The color of the bubbles in Figure 2 represents the $D$ value in a temperature map, starting with the blue for the smallest values and ending with the deep red for the largest. We observe some tendency of most extreme extra noise parameters to occur at small separations.

3. Astrometric Errors

As explained in Lindegren et al. (2016), Mignard et al. (2016), and Makarov et al. (2017), the covariances of bivariate parameters should be used when comparing data in two independent catalogs and estimating the statistical significance of the differences. In our case, the positions and proper motions in both the Hipparcos and Gaia catalogs have complete covariance matrices, including nonzero correlations. For example, if we want to estimate the statistical significance of a proper motion difference vector $\Delta p = p_{\text{Gaia}} - p_{\text{HIP}}$, where $p_{\text{HIP}} = [\mu_\alpha, \mu_\delta]_\text{HIP}$ is the proper motion vector composed of the tangential components in R.A. and decl., provided in the Hipparcos catalog (and likewise for Gaia), the variance-normalized quadratic difference is computed as

$$u_p = \Delta p \mathbf{C}^{-1} \Delta p^T,$$

where $\mathbf{C}$ is the total covariance matrix of the difference vector, $\mathbf{C} = \mathbf{C}_{\text{Gaia}} + \mathbf{C}_{\text{HIP}}$. The quadratic form $u$ is $\chi^2$-distributed with 2 degrees of freedom if the measurements are normally distributed. Normalized differences of positions can be computed in a similar way, making sure that the correct $2 \times 2$ blocks of the $5 \times 5$ formal covariance matrices are taken. For each star, the $u$ statistic is a random number. The sample distribution of a set of $u$ values allows us to assess how closely the formal errors estimate the actual uncertainty of the data. Since parallaxes are univariate statistics, their variance-
normalized differences are computed simply by

\[ u = \frac{(\bar{x}_{\text{Gaia}} - \bar{x}_{\text{HIP}})^2}{\sigma_{\bar{x}, \text{Gaia}}^2 + \sigma_{\bar{x}, \text{HIP}}^2}, \]

and the sample distribution is expected to be close to the \( \chi^2 \) distribution with one degree of freedom.

Figure 3 shows the probability plots of the \( u \) statistics for the proper motion (left) and parallax (right) differences between TGAS and Hipparcos for the 1124 components of double stars resolved by Hipparcos. A probability plot is a way of graphically representing any differences between a sample distribution and an expected theoretical distribution, where the sample cumulative distribution function (CDF) is mapped versus the theoretical CDF. For a perfect match of the distributions, the ordered sample quantiles should lie on the diagonal, which is marked with a dashed line. We find in both cases a definite departure from the expectancy. For all parallaxes, and for 70% of the smaller normalized differences in proper motions, the curves buckle up. This means that the observed scatter of the differences is smaller than the formal errors suggest. In other words, all parallax errors, and many of the proper motion errors, are overestimated. This result is puzzling, as formal errors are usually underestimated in astrometric catalogs because it is difficult to take into account systematic and correlated errors. The largest 30% of proper motion differences, on the other hand, are too large compared with the expected probability. This is what we should expect if the astrometric data are additionally perturbed by the duplicity, which frequently remained unresolved in Gaia DR1.

Formal standard errors were inflated a posteriori in TGAS in an attempt to account for sources of uncertainty apart from the photon statistics (Lindegren et al. 2016). The inflation factor (greater than 1.4) is a function of only the parallax formal error; therefore, this manipulation can be reversed. To clarify our results for this external comparison, we deflated the parallax errors and re-constructed the probability plots. The resulting curve is slightly closer to the diagonal compared to Figure 3 (right), but the sample distribution is still confidently deviant from CDF$_{\chi^2[1]}$. This is because the formal errors in TGAS are typically smaller than the errors in Hipparcos, and scaling the former down in the denominator of Equation (2) does not help much. We further extended our comparison to the general TGAS-HIP sample. A similar probability plot for 78,755 bona fide single stars (without any signs of binarity or other known perturbations), not reproduced in this Letter, is the opposite to Figure 3 (right), in that the curve is systematically below the diagonal for the entire interval of cumulative probability. The conclusion is inescapable: the formal errors of parallaxes and most proper motions are overestimated for double star components, but underestimated for bona fide single stars. The only credible explanation we can find is that the Hipparcos formal errors were artificially inflated for double stars in the special component solution and, apparently, too much.

This makes finding any additional noise in TGAS data rather difficult. The position differences are practically useless because we would have to compare positions separated by 23.75 years and bridged by the proper motion, which was derived using the same positions. This inconvenience opens up another opportunity though. We expect the TGAS positions of unresolved pairs to be displaced toward the photocenters located on the lines connecting the components. The amount of displacement depends on the \( \Delta \text{mag} \) in the \( G \) passband (in which the astrometric observations were taken) and the separation. They can be large running up a fraction of 1\(^\circ\). These photocenter shifts should perturb the TGAS proper motions, but only in the directions of double systems, by up to \( \sim 25 \) mas yr\(^{-1}\), which should be easily detectable in the Gaia-HIP differences. Thus, our task now is to compute the normalized proper motion differences in the \( s^- \) (along the lines
connecting the components) and the c-direction (orthogonal) for each pair.

This task is performed as follows. Let $\theta$ be the position angle of the double as specified in DMSA. The $s$-direction is then defined as the unit vector $s = [\sin \theta, \cos \theta]$, and the orthogonal direction is $c = [\cos \theta, -\sin \theta]$. The sought normalized difference components $u_s$ and $u_c$ are computed by Equation (1) replacing the proper motion difference vector $\Delta_p$ with its projections $(\Delta_p \cdot s)s$ and $(\Delta_p \cdot c)c$, respectively. These statistics are expected to be distributed as $\chi^2$ with one degree of freedom.

Figure 4 shows the resulting probability plot for $u_s$ (blue curve) and $u_c$ (golden curve) for all pairs with separations less than $1\,''2$, which are mostly unresolved in Gaia DR1. This tighter threshold is chosen to emphasize the difference between the components, which is more obvious for smaller separations, as we will see in the following. While the orthogonal components of proper motion differences show little perturbation and are distributed similarly to the overall sample, the aligned components display a very strong additional scatter. To make sure that it is not a mere trick of the eye, we computed six different hypothesis tests on the sample distributions comparing them with the $\chi^2[1]$. The $p$-values from all six tests are very small for the $s$-components, with the largest value 0.0016 produced by the Kuiper’s test. On the contrary, the $p$-values for the $c$-components are significant, with $p = 0.61$ from the Pearson’s $\chi^2$ and $p = 0.55$ from the Kolmogorov–Smirnov test. This obvious difference in dispersion of components disappears if we reproduce this analysis for all pairs with separations greater than $1\,''5$. In fact, the $s$-components are slightly less dispersed than the $c$-components. Thus, no detectable perturbation in Gaia DR1 astrometry emerges for wider double stars, which are mostly resolved.

Since the photocenters of unresolved double stars in TGAS are shifted from the primaries toward the secondaries, the errors in the $s$-components of TGAS proper motions should be predominantly positive. This is nicely confirmed in Figure 5 where the HIP–Gaia $s$-component differences are displayed for the smallest separations available in the TychoBV sample. The effect of unresolved duplicity dramatically increases toward the smallest separations, which is a predictable consequence of the implemented scheme of PSF centroiding. Despite the random errors somewhat blurring the picture, the great majority of differences are negative at separations below $0\,''4$, and the error can reach 15 mas yr$^{-1}$ in absolute units. Pairs of small magnitude difference (blue bubbles) tend to produce larger proper motion errors in TGAS, as expected. The dashed line shows the expected proper motion difference for TGAS entries that were mistakenly cross-matched with the secondary components instead of the primaries (swapped components), i.e., the separation divided by 23.75 with the negative sign. Two stars in this range of separation are close to this line and are likely to be such swapped pairs.

4. Conclusions

We have detected, with practically absolute confidence, a strong perturbation of Gaia DR1 positions along the lines...
connecting components of unresolved doubles, which resulted in corrupted proper motion components in the corresponding directions. From the general rate of resolved double and multiple stars in *Hipparcos* (10%) and the rate of doubles in the TGAS solution, we estimate that 3% or more of the entries in *Gaia* DR1 should be affected by unresolved duplicity. The parallaxes, on the other hand, do not show any degradation in accuracy, although this resilience could be explained to some extent by artificially inflated formal errors in the *Hipparcos* component solution. We also find that 1.5 is roughly the threshold separating mostly resolved doubles from mostly unresolved at brighter magnitudes, although this boundary is rather fuzzy. When a pair of stars is resolved (with the primary in TGAS and the secondary in the main catalog), the astrometric parameters of the primary seem to be unaffected within the uncertainties of the two catalogs.

Swapped or misidentified companions represent another source of crude errors in *Gaia* DR1. The rate of these can be estimated using the *s*-components of proper motion differences in *Hipparcos* and *Gaia*, which should be close to the separation (as determined by *Hipparcos*) divided by the epoch difference, 23.75 years. Selecting the differences within ±3 mas yr⁻¹ of that value for the entire collection of 1124 pairs, we find 4 credible cases of such misidentified components, namely, HIP 23317, 50305, 67186, and 114504. The largest separation, and hence the proper motion error, is found for the HIP 50305 (1.409). The estimated rate of such misidentifications is approximately 0.4% for the collection of *Hipparcos* resolved doubles.

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**References**

Arenou, F., Luri, X., Babusiaux, C., et al. 2017, A&A, 599, A50
Berghea, C. T., Makarov, V. V., Frouard, J., et al. 2016, AJ, 152, 53
Bessell, M. S. 2000, PASP, 112, 961
Brown, A. G. A. & Gaia Collaboration 2016, A&A, 595, A2
ESA 1997, The Hipparcos Catalogue (ESA SP-1200; Noordwijk: ESA)
Fabricius, C., Bastian, U., Portell, J., et al. 2016, A&A, 595, A3
Fabricius, C., & Makarov, V. V. 2000, A&A, 144, 45
Frouard, J., Dorland, B. N., Makarov, V. V., Zacharias, N., & Finch, C. T. 2015, AJ, 150, 141
Høg, E., Fabricius, C., Makarov, V. V., et al. 2000a, A&A, 357, 27
Høg, E., Fabricius, C., Makarov, V. V., et al. 2000b, A&A, 357, 367
Lindegren, L., Lammers, U., Bastian, U., et al. 2016, A&A, 595, A4
Makarov, V. V., Frouard, J., Berghea, C. T., et al. 2017, ApJL, 835, L30
Mignard, F., Klioner, S., Lindegren, L., et al. 2016, A&A, 595, A5
van Leeuwen, F. 2007, Hipparcos, the New Reduction of the Raw Data (Dordrecht: Springer)