htof: A New Open-source Tool for Analyzing Hipparcos, Gaia, and Future Astrometric Missions

G. Mirek Brandt1,5, Daniel Michalik2,6, Timothy D. Brandt1,6, Yiting Li1,6, Trent J. Dupuy3, and Yunlin Zeng1,4

1 Department of Physics, University of California, Santa Barbara, Santa Barbara, CA 93106, USA; gmbrandt@physics.ucsb.edu
2 European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
3 Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, UK
4 School of Physics, Georgia Institute of Technology, 837 State Street, Atlanta, GA, USA
5 NSF Graduate Research Fellow.
6 ESA Research Fellow.

Received 2020 October 18; revised 2021 June 29; accepted 2021 July 7; published 2021 November 5

Abstract

We present htof, an open-source tool for interpreting and fitting the intermediate astrometric data (IAD) from both the 1997 and 2007 reductions of Hipparcos, the scanning law of Gaia, and future missions such as the Nancy Grace Roman Space Telescope (NGRST). htof solves the astrometric parameters of any system for any arbitrary combination of absolute astrometric missions. In preparation for later Gaia data releases, htof supports arbitrarily high-order astrometric solutions (e.g., five-, seven-, and nine-parameter fits). Using htof, we find that the IAD of 6617 sources in Hipparcos 2007 might have been affected by a data corruption issue. htof integrates an ad hoc correction that reconciles the IAD of these sources with their published catalog solutions. We developed htof to study masses and orbital parameters of substellar companions, and we outline its implementation in one orbit fitting code (orvara). We use htof to predict a range of hypothetical additional planets in the β Pic system, which could be detected by coupling NGRST astrometry with Gaia and Hipparcos. htof is pip installable and available at https://github.com/gmbrandt/htof.

Unified Astronomy Thesaurus concepts: Space astrometry (1541); Astrometry (80); Astronomical techniques (1684); Parallax (1197); Astronomy software (1855); Open source software (1866); Exoplanet detection methods (489); Exoplanet astronomy (486); Exoplanets (498)

1. Introduction

Astrometric missions like Hipparcos or Gaia measure absolute positions, parallaxes, and motions for the stars that they survey (Perryman 2012). These missions observe a star many times and fit a model to that star’s motion in the plane of the sky, also known as the star’s ephemeris. A star’s apparent motion is most simply modeled as parallactic motion (motion induced by the earth’s orbit) together with a constant velocity, encoded in five parameters. The Hipparcos (Perryman et al. 1997; van Leeuwen 2007a) and Gaia (Gaia Collaboration et al. 2016, 2018a, 2021; Lindegren et al. 2018) catalogs report the five best-fit astrometric parameters: two position parameters at a reference epoch, two proper motions, and the parallax. The five-parameter astrometric model, however, is only an approximation; even a single star with a constant 3D velocity exhibits apparent accelerations when its motion is projected into spherical coordinates (perspective acceleration; Michalik et al. 2014; Lindegren & Dravins 2021). Stars may also accelerate due to visible and/or unseen companions, or even due to their orbits through the Galaxy.

The influence of unseen companions may be modeled as a higher-order astrometric fit with seven or nine parameters, or as a full-Keplerian orbit. The first full orbital fits of Hipparcos astrometry were done by the Hipparcos team themselves (Lindegren et al. 1997). Work over the following decades built on this work to include brown dwarfs and giant planets (e.g., Zucker & Mazeh 2001; Sozzetti & Desidera 2010; Reffert & Quirrenbach 2011; Sahlmann et al. 2011; Snellen & Brown 2018). The most recent additions to this field are covering harder to detect and less massive exoplanets, leveraging the long-term proper motion anomalies between Hipparcos and Gaia (Brandt 2018; Brandt et al. 2019, 2021a; Calisendorff & Janson 2018; Dupuy et al. 2019; Feng et al. 2019; Fontanive et al. 2019; Kervella et al. 2019; Currie et al. 2020; Maire et al. 2020).

For companions with orbital periods ≤10 yr, proper motion accelerations within Hipparcos and Gaia become important to model. The intermediate astrometric data (hereafter, IAD) of the Hipparcos mission—the individual position measurements and uncertainties for every star—are available. The Gaia IAD for every star will be unavailable for many years, but the spacecraft’s scanning law—its predicted scan angles and observational epochs as a function of sky position—is available through the Gaia Observation Forecast Tool (GOST; Fernández-Hernández & Joliet 2019). Several groups have used GOST predictions to forward model Gaia astrometry in the context of orbit fitting (e.g., Brandt et al. 2020; Nielsen et al. 2020; De Rosa et al. 2020).

In this paper, we present a tool, htof (Brandt et al. 2021c), that uses the IAD for Hipparcos and the scanning law of Gaia to fit sky paths. Although htof extends beyond the hundred thousand sources of Hipparcos, htof stands for the Hundred Thousand Object Fitter in homage to the hundred-thousand-proper-motion project (de Bruijne & Eilers 2012; Michalik et al. 2014). For both Gaia and Hipparcos, htof can compute fits with arbitrarily many parameters, e.g., five-, seven-, and nine-parameters. Given the Hipparcos IAD for a star, htof computes likelihoods and parameter errors directly comparable to the catalog values for that star. For Gaia, htof is currently limited to approximate likelihoods and errors because the actual observations and their uncertainties are not yet available.

https://gaia.esac.esa.int/gost/
htof’s capabilities make it well suited for exploring many problems such as simulating the planets which could be discovered by future astrometric missions. The likelihoods computed by htof also enable full-Keplerian orbital fits if combined with common-reference-frame and cross-calibrated positions and errors from Hipparcos and Gaia, e.g., from the Hipparcos-Gaia Catalog of Accelerations (Brandt 2018). htof was used in a number of papers exploiting the latter technique for studying dynamical masses and orbital parameters of substellar companions in nearby stellar systems (Brandt et al. 2020, 2021b; Bowler et al. 2021a, 2021b).

This paper is structured as follows. In Section 2, we describe Gaia, Hipparcos, fitting astrometry, and parsing the IAD. In Section 3, we discuss htof along with its implementation, validation, and limitations. In Section 4, we discuss a suspected data corruption affecting 6617 sources in the Hipparcos 2007 IAD. We have developed an ad hoc correction algorithm to recover their best-fit residuals. It is readily integrated in htof. We then discuss two major use cases. We outline htof’s utility in orbit fitting in Section 5. In Section 6, we demonstrate how htof can predict what new planets could be discovered by combining Gaia astrometry with measurements from the Nancy Grace Roman Space Telescope (NGRST; Spergel et al. 2015). We summarize our results in Section 7.

2. Observing and Fitting an Astrometric Sky Path

Gaia and Hipparcos observe stars by scanning the sky in a repetitive pattern, which is called the scanning law (van Leeuwen & Evans 1998; Gaia Collaboration et al. 2016). For both satellites, the continuous scans along overlapping great circles mean that each observation is precise in the direction along the scan (along-scan; AL), and imprecise perpendicular to the scan (across-scan; AC). This renders each observation effectively one-dimensional (Gaia Collaboration et al. 2016). Figure 1 shows the definitions we use for the scan angle $\psi$ of the observation and the abscissa residual, consistent with the definitions given in Gaia Collaboration et al. (2018b) and online. The scan angle $\psi$ of the 2007 Hipparcos re-reduction is defined differently than for Gaia, but this is handled by a conversion discussed in Section 2.2.2. In Figure 1, the spacecraft spin direction is indicated by the AL arrow, the spin axis is perpendicular to it in the AC direction. This (essentially one-dimensional) error ellipse of an observation is indicated by the red double-headed arrow. Hipparcos and Gaia fit sky paths to the abscissa residuals; the model sky paths are collectively referred to as the astrometric solution. The shortest distance between the prediction of the best-fit astrometric model at the observational epoch and the 1D observed position is called the abscissa residual $\nu$.

The astrometric solution for a given star is the set of model parameters that minimizes the sum of the squared AL abscissa residuals weighted by the inverse of the AL variances. A good astrometric solution requires data with good geometric and temporal coverage, i.e., many different scan angles at many different epochs. In the following subsections, we discuss how to obtain the best-fit astrometric parameters from the IAD.

2.1. Fitting the Sky Path

For a five-parameter astrometric model, the observed position on the sky is the sum of the parallaxes, proper motion, and position multiplied by known functions of time. Higher-order models include acceleration and jerk terms. Fitting the ephemerides under five-, seven-, or nine-parameter models is a linear problem, and may be solved by minimizing the chi squared of the abscissae with respect to the astrometric parameters. The chi-squared minimization problem can be transformed into a matrix equation that can then be solved by any standard linear algebra method, e.g., singular value decomposition in htof. The model for the star’s motion across the sky that we adopt is

$$\alpha_{m,i} = \psi f_\alpha \,[t_i] + \sum_{n=0}^{N} \frac{a_n}{n!} (t_i - t_\text{ref})^n$$

$$\delta_{m,i} = \psi g_\delta \,[t_i] + \sum_{n=0}^{N} \frac{b_n}{n!} (t_i - t_\text{ref})^n$$

(1)

where $(\delta_{m,i}, \alpha_{m,i})$ is the predicted model decl. and R.A. at time $t_i$. $a_n$, $b_n$ are the astrometric parameters excluding parallax (e.g., $b_1 = \mu_\alpha$), N is the degree of the fit ($N=1$ for a five-parameter fit), $\psi$ is the parallax angle, and $f_\alpha \,[t_i]$, $g_\delta \,[t_i]$ are the parallax factors (van Leeuwen 2007b). These are the perturbations in decl. and R.A., respectively, due to parallax alone for a parallax angle of unity. $f_\alpha \,[t_i] \cos(\theta_\text{scan}) + g_\delta \,[t_i] \sin(\theta_\text{scan})$ is equal to $\frac{\delta_{m,i}}{\psi}$, the derivative of the residual with respect to parallax. We use modules from astrometric-sky-path to compute the parallax factors.

The Hipparcos catalog abscissa residuals $\nu_i$ are with respect to the AL direction only (for both the 1997 and 2007 catalogs).

---

*8 https://www.cosmos.esa.int/web/gaia/scanning-law-pointings

*9 https://github.com/agabrown/astrometric-sky-path
The matrix equation can be constructed, and in turn the best-fit astrometric parameters can be solved, purely in terms of the AL derivatives and abscissa residuals (Perryman et al. 1997). Alternatively, one can first cast the measurements into the equatorial coordinate system and construct the matrix equation from those R.A. and decl. observations. The former approach is closer to how the Hipparcos team handled the data (Perryman et al. 1997), while htof uses the latter approach, whereby we minimize Equation (2). The two are equivalent, but we employ the latter because then the input data are more familiar: R.A. and decl. instead of AL abscissa residuals and derivatives.

We therefore assume that we have: the covariance matrix \( C_i \) for an observation \( i \) that occurred at epoch \( t_i \) and the corresponding R.A. \( \alpha_i \) and decl. \( \delta_i \). We obtain the \( \delta_i, \alpha_i \) by decomposing each abscissa residual \( \nu_i \) into the two equatorial components. We find the best-fit astrometric parameters by minimizing

\[
\chi^2 = \sum_i (\alpha_{m,i} - \alpha_i, \delta_{m,i} - \delta_i)C_i^{-1}(\alpha_{m,i} - \alpha_i, \delta_{m,i} - \delta_i).
\]  

In detail, the parallactic motion of any object with a nonzero proper motion will change as it moves through the sky. The parallax factors are functions of position as well as time. Nonlinear effects such as perspective acceleration are negligible for most stars. For example, Lindegren et al. (2018) lists only 53 stars where nonlinear effects warrant correction, one of which is Barnard’s star (\( \mu \approx 10^\circ \) yr\(^{-1} \); van de Kamp 1935; Luyten 1979). We therefore always assume that the model (Equation (1)) is linear.

We solve for the best-fit parameters by taking the partial derivative of Equation (2) with respect to each of the free parameters. The partials yield a matrix equation of full rank (e.g., a 9 \( \times \) 9 matrix if \( N = 3 \) in Equation (2)), which is linear in every parameter. We solve for the best-fit parameters with singular value decomposition.

### 2.2. Obtaining Astrometry from Hipparcos IAD and the Gaia Scanning Law

To recover a solution for each source we need the epochs of observation, the source’s position in the sky at each epoch, and the covariance matrix of the observation at each epoch. In this section, we detail how to obtain and parse those quantities from Hipparcos and Gaia.

For both Hipparcos reductions, the IAD are enough to calculate full positions and covariance matrices. For Gaia, we use the predicted scanning law as a proxy for the IAD. We calculate positions assuming the Gaia catalog astrometric parameters, and calculate the epochs and covariance matrices for each observation.

Table 1 summarizes how to extract the scan angles, observation times and AL errors from the IAD from both Hipparcos reductions and the Gaia scanning law. Each variable and column in Table 1 is named in accordance with each astrometry product. We now turn to details of the IAD and the scanning law.

#### 2.2.1. The Original (1997) Hipparcos Catalog

The IAD for the original Hipparcos catalog (Perryman et al. 1997) are available from the Strasbourg Astronomical Data Center FTP archive.\(^\text{10}\) The IAD give the scan angles, abscissa residuals relative to the first five parameters of the best-fit sky path, formal AL errors for each observation, and time of observation. Each file from the IAD has ten columns, referred to in the documentation as IA1 through IA10. In the second column (IA2), each row is labeled either \( N \) or \( F \) for NDAC for FAST, depending on which consortium reduced the data. The formal AL errors (\( \sigma_\text{AL} \)) are in column IA9 and the abscissa residuals are given in column IA8. The scan angle is arctan\( _2 \) (IA3, IA4) (van Leeuwen & Evans 1998).

The astrometric parameters in the original Hipparcos catalog are those that best fit the merged IAD. We merge the NDAC and FAST IAD following the procedure described by the Hipparcos team (see Section 3.2 of van Leeuwen & Evans 1998). For each epoch that contains both NDAC and FAST data, we average the values from both consortia weighted by best-linear- unbiased-estimator weights. These weights, a pair per epoch, are determined uniquely by the covariance matrix constructed according to Equation (7.11) on page 377 of Volume 3 of Perryman et al. (1997), using the NDAC-FAST correlation coefficient in column IA10. We exclude observations rejected from the Hipparcos merged solution (Perryman et al. 1997), which are designated by a lowercase letter in the consortium designation.

#### 2.2.2. The 2007 Re-reduction of the Hipparcos Data

Ten years after the publication of the original Hipparcos catalog, van Leeuwen (2007a) re-reduced the raw data to produce new astrometric fits. At the time of writing, there are three sets of the Hipparcos re-reduction catalog. First, and oldest, is the Digital Versatile Disk (DVD) included with van Leeuwen (2007a), which contains the first published version of the catalog as well as the IAD used to construct it. Second is the Vizier catalog\(^\text{11}\) which does not include the IAD. Third, and most recent, is the data distributed with a Java tool.\(^\text{12}\) This tool includes the IAD but not in per-source human readable data files as are on the DVD. We have extracted the IAD from the Java tool (van Leeuwen & Michalik 2019\(^\text{13}\)). All three sources give data that are similar for every star, yet not identical. One must consistently use the IAD together with the catalog it
accompanied. For example, one should not mix catalog values from Vizier with the IAD from the DVD. For most sources, results using the IAD from the DVD are indistinguishable from results using the IAD from the Java tool. One advantage of the Java tool data is that rejected transits are clearly denoted by negative AL errors. Rejected observations are not designated in the DVD IAD.

The columns of the residual records of the 2007 IAD (both the DVD and Java tool) are defined in Table G.8 of van Leeuwen (2007b). The fourth column gives $\cos(\Psi) = \sin(\theta)$, and the fifth column gives $\sin(\Psi) = \cos(\theta)$, where $\theta$ is the scan angle and $\Psi = \pi/2 - \theta$. We index the first column as 1 to be consistent with the original reduction’s documentation. The AL errors are given in column 7 for the re-reduction. The abscissa residuals are in column 6. For sources with seven and nine parameter solutions, the residuals in the Hipparcos 2007 IAD are relative to the full seven or nine parameter solutions. This is in contrast to Hipparcos 1997 where the residuals are defined with respect to the sky path described by only the first five parameters, regardless of solution type.

2.2.3. The GOST

Gaia Data Release 1 (DR1), DR2, and EDR3 (Gaia Collaboration et al. 2016, 2018a, 2021; Lindegren et al. 2018) contain model parameters (positions, proper motions, parallaxes, and their uncertainties and covariances), but neither the epoch astrometry, the AL residuals, nor the per-epoch covariance matrices. The full epoch astrometry will be released in the final catalog of the nominal mission.14 htof uses GOST as a stand-in for these data. GOST provides predicted observations and scan angles for any Gaia source. The GOST data should be downloaded manually as a .csv (see the readme with the htof source code), but a future version of htof may automate this. htof places the GOST data into a suitable form for fitting as if they were the Gaia IAD. GOST-predicted scans, parsed by htof, are used in a variety of orbital analyses of brown dwarf companions to help constrain companion masses and orbital inclinations. For instance Brandt et al. (2020, 2021b) and Bowler et al. (2021a, 2021b). However, there are important details to consider with the planned observations.

Not all of the planned observations will be used in the astrometric solution. Some predicted scans will represent missed observations (satellite dead times), executed but unusable observations (e.g., from cooldown after decontamination), or observations rejected as astrometric outliers. Rejected observations could be corrupted due to, e.g., microclanks, scattered light from a nearby bright source, crowded fields, micrometeoroid hits, etc.15 Such problematic observations do not constrain the Gaia astrometric solution. In practice, up to 20% of Gaia observations predicted by GOST are excluded from the analysis that produced DR2 (ESA 2020). The largest stretches of dead times and rejected observations are published as astrometric gaps. htof accounts for the published astrometric gaps for DR2,16 and EDR3 (Table 1 of Lindegren et al. 2021).

2.3. Constructing the Covariance Matrix for Each Observation

We need the inverse covariance matrix for every observation, $C_i^{-1}$, to evaluate and minimize $\chi^2$ (Equation (2)). We construct $C_i^{-1}$ from the scanning law or the IAD. We define the ratio of the AC to AL variances as $r$ and assume these two measurements to be independent. By default, htof has $r = \infty$ because Hipparcos and Gaia both optimize for AL. For Hipparcos, we have the individual AL uncertainties for all observations. For Gaia, we do not and so we assume the AL error to be the same for all epochs of a given source. The covariance matrix at each epoch is then correct up to a (unknown) constant (the AL error).17

Given a scan angle $\theta_i$, $r$, and AL error $\sigma_{AL,i}$, for the $i$th observation, we construct the covariance matrix $C_i$ by rotating the covariance matrix in the scan basis into the equatorial coordinate system as follows.

$$C_i = \sigma_{AL,i}^2 R_i(\theta_i) \begin{pmatrix} 1 & 0 \\ 0 & r \end{pmatrix} R_i^T(\theta_i)$$

where $R_i(\theta_i) = \begin{pmatrix} \sin \theta_i & -\cos \theta_i \\ \cos \theta_i & \sin \theta_i \end{pmatrix}$.

In Equation (3), $R(\theta)$ is the inverse of the transformation matrix in Equation (3) of Gaia Collaboration et al. (2018b) and $R^T(\theta)$ its transpose. For Gaia, we assume uniform AL errors and set $\sigma_{AL,i}$ to unity for every observation of a given source. We multiply each Hipparcos re-reduction $\sigma_{AL}$ by the scaling factor $u$ in Equation B.4. of Michalik et al. (2014). This is a renormalization to match van Leeuwen (2007b), where the errors were normalized such that the reduced $\chi^2$ of the fit was unity. The inverse covariance matrix is

$$C_i^{-1} = \frac{1}{\sigma_{AL,i}^2} R_i(\theta_i) \begin{pmatrix} 1 & 0 \\ 0 & 1/r \end{pmatrix} R_i^T(\theta_i)$$

where $1/r = 0$ for Hipparcos and by default in htof. With the inverse covariance matrix for each observed R.A. $\alpha_i$ and decl. $\delta_i$, we generate the astrometric model that best fits those observations according to Section 2.1.

3. htof

htof is an open-source Python package available at https://github.com/gmbrandt/htof that parses and fits astrometric data according to the methods discussed in Section 2.

3.1. User Guide and Core Features

htof is designed to fit five-, seven-, and nine-parameter models to any Hipparcos or Gaia source. It can calculate the full covariance matrix of the fit, calculate central epochs of observation, perform an ad hoc correction of the 2007 IAD for 6617 sources, and combine astrometric missions (useful for forecasting: Section 6). It possesses a variety of other minor features. htof does not provide an automated download (as of version 1.0.0) of the Hipparcos IAD (either reduction) or Gaia GOST data. These data must be downloaded manually.

htof can analyze data from arbitrary astrometric missions. htof is centered around DataParser subclasses that parse the IAD or scanning law into scan angles, errors, etc., and a single AstrometricFitter class that generates an astrometric solution from data within any of the numerous DataParser subclasses. The DataParser classes hold

---

14 See footnote 14.
15 See Section 6.1.1 of Brandt et al. (2021b) for a discussion of the limitation of the uniform AL error assumption in the context of Gl 229.
the data in a consistent way so that the single fitter class, AstrometricFitter, can fit an astrometric sky path. There is also a convenience Astrometry class that wraps all the functionality of the data parser and fitting classes. For examples of fits and other functionality, we refer the reader to the documentation readme and the Jupiter example notebook that is packaged with the source code. In the following, we review htof’s core functionality of astrometric fitting.

Astrometry.fit(ra, dec) returns an array of the best-fit astrometric parameters. If the fit degree is 1 and Astrometry is instantiated with use_parallax=True, this array will be \((\alpha_0, \beta_0, \mu_{\alpha,\circ}, \mu_{\delta})\), the parallax angle, the R.A. and decl. (relative to the reference R.A. and decl. provided to Astrometry()), the proper motion in R.A., and the proper motion in decl.—by default with units of mas and mas yr\(^{-1}\). If fit (ra, dec, return_all=True) is used, then the fit will return the best-fit parameter array, an array of the standard errors of each parameter, and the formal chi-square of the fit. The AstrometricFitter can provide the full covariance matrix if it is desired (not just the errors on each parameter); examples of this are in the Jupiter notebook with the source code.

Fitting requires providing a reference epoch around which to center the observations. For Hipparcos 1997 catalog solutions, the consortia used J1991.25. The choice of reference epoch will affect the values, errors, and covariances for all but the highest-order terms in any fit. For example, changing the reference epoch for a five-parameter fit will affect the fitted reference positions, their errors, and covariances; but not the proper motions. Choosing a reference epoch far away from the optimal epoch (e.g., choosing the year 1000 for Hipparcos instead of 1991.25) will result in numerical instability and a poorly constrained solution.

3.2. Validation of the Fits to the Hipparcos IAD

htof can reproduce the catalog solutions for the vast majority of sources in both Hipparcos reductions from the IAD. At the time of this publication, htof is designed for sources with five-, seven-, or nine-parameter solutions, from both Hipparcos reductions. Future versions of htof may incorporate sources with VIM (V), stochastic (X), component (C), or orbital (O) solutions. We point the reader to the readme with the source code for the up-to-date capabilities of the code.

In the current version (1.0.0), there is a subset of the Hipparcos five-, seven-, and nine-parameter sources for which the best-fit htof parameters disagree slightly with the catalog values. For the vast majority of sources, htof matches the catalog values either exactly after rounding, or with a scatter that is attributable to roundoff within the IAD. We found that offsets up to \(\pm 0.01\) mas yr\(^{-1}\) in both R.A. or decl. could be attributed to round off based on Monte Carlo simulations of randomly selected disagreeing sources. There are only a small number of sources that htof cannot fit well: 120 sources disagree more than 0.1 mas yr\(^{-1}\) in proper motion in either direction. We label these 120 sources as “flagged” and provide a list of them in the file htof/data/hip1_flagged.txt. A 0.1 mas yr\(^{-1}\) disagreement is typically less than 1/2 of a standard error for the discrepant sources. The fraction of discrepant sources is similar for the Hipparcos 2007 re-reduction, but only after applying our proposed ad hoc correction to the IAD.

4. Ad Hoc Correction to 6617 Sources in Hipparcos 2007

Hipparcos 2007 was a momentous effort largely by one individual. It is and remains an invaluable record of stellar astrometry. As with every data set, deeper analysis sometimes reveals new ways of interpreting the data. Here we propose an improvement to the Hipparcos 2007 IAD.

We found 6617 sources from Hipparcos 2007 for which the astrometric solution implied by the IAD is significantly discrepant with the published catalog parameters. Two examples are HIP 651 and 44050. Discrepant sources are present both in the Java tool and in the DVD IAD. The subset of discrepant sources is almost, but not exactly, identical between the two. However, we limit our discussion of the issue and our ad hoc correction to the IAD from the Java tool. The Java tool includes a clear designation of rejected transits. Without knowing the regularly rejected transits, our ad hoc correction algorithm becomes combinatorially unfeasible. There is ongoing work to understand these 6617 sources in more detail (van Leeuwen & Michalik 2021).

To identify the issue, we first read in the IAD for every Hipparcos source. We compute the partial derivatives of \(\chi^2\) with respect to each of the astrometric parameters, normalized by the standard errors to make them dimensionless (e.g., \(\frac{\partial \chi^2}{\partial \mu_{\alpha,\circ}}\)). If the residuals from the IAD correspond to a solution that minimizes \(\chi^2\), then these partials will all be zero within roundoff error. For most sources, the quadrature sums of the scaled partial derivatives are indeed nearly zero, ranging from \(10^{-2}\) to \(10^{-7}\). For the 6617 sources that we cannot refit, these partial derivative sums are significantly nonzero (e.g., \(>1\)) implying that the best-fit residuals (data minus model) listed in the IAD are not the residuals with respect to the model that minimizes \(\chi^2\). As another check, we also refit the IAD with the appropriate astrometric model (five-, seven-, or nine-parameters) and compare the refit proper motions to those in the catalog. The refit proper motions do not match the catalog values for the discrepant sources.

The top panel of Figure 2 displays the quadrature sum of the chi-squared partials for all five-parameter sources, along with the difference between our refit proper motion and the catalog proper motions. The 6617 sources (colored in red) form a clear outlier cloud.

The culprit of the nonreproducibility of these 6617 sources appears to be data corruption in the IAD. Almost all of the discrepant sources have one or more lines of repeating AL errors at the end of their IAD file. The number of repeats, \(n\), varies from source to source. For example, HIP 12241 has as the last four AL errors (in mas): 4.92, 4.10, 4.92, and 4.10. For HIP 42975 and 21000, the last ten AL errors are repeated in the same sequence. A second clue comes from the IAD header, which states the number of observations considered for the astrometric solution of a given source. For the problematic sources this number is \(n\) less than the number of residual records available in the IAD file. This discrepancy persists even after removing transits marked as rejected by negative AL errors. An example is HIP 651, where the IAD header states 164 observations considered, but the residual records contain 165 transits. The mismatch between observations considered and residuals available is 1 for 5919 of these 6617 sources, 419 have \(n = 2\).

Deleting the last \(n\) rows does not resolve the issue. We suspect instead that an additional \(n\) transits were supposed to be removed at some stage of the astrometric processing, but were
sources are blue. Upper panel: the results of the re

correction. Lower panel: all

of the former outliers that we applied our algorithm to

Distributions of the proper motion difference and quadrature sums of

Figure 2. Distributions of the proper motion difference and quadrature sums of partial derivatives of fits to the Hipparcos Java tool IAD before (top panel) and after (bottom panel) the htof IAD ad hoc correction. All 115,100 five-parameter sources are shown. The vertical axis shows the quadrature sum of the proper motion discrepancy (difference between the catalog values and the values obtained by refitting the IAD). The horizontal axis shows the five partial derivatives of chi-squared ($\chi^2$) also added in quadrature: $\sqrt{(\sigma_{a_r} \partial \chi^2 / \partial a_r)^2 + (\sigma_{a_\phi} \partial \chi^2 / \partial a_\phi)^2 + \ldots}$.

The 6617 sources with a suspected IAD corruption are colored red, otherwise sources are blue. Upper panel: the results of the refit without htof’s ad hoc correction. Lower panel: all five-parameter sources, after our ad hoc correction. All of the former outliers that we applied our algorithm to (all but 38) are now well-behaved and a fit of their IAD yields the catalog solution (blue and red data points overlap).

is removed, except for 38 sources where the ad hoc correction is combinatorially infeasible. Refitting the modified IAD always recovers the catalog parameters. This strongly supports that our algorithm is correct and that the 6617 outliers that we discovered were caused by data corruption in their IAD.

We do not apply our ad hoc correction to 38 sources because $n$ is so great for these sources that our ad hoc correction requires an inordinately large computation time. GI 660 (HIP 84123) is among these 38, which has $n = 21$ (which would take roughly 200 days on a single CPU core to correct). A list of the 38 outliers that we do not correct are listed in htof/data/hip2_Javatool_flagged.txt. htof applies the ad hoc correction automatically to any IAD from the Java tool, except these 38 sources.

This fix is important for many uses of the IAD. Many Hipparcos sources host planetary or brown dwarf companions, and the masses of these companions can be measured by fitting the proper motion anomalies derived from five-parameter fits to the IAD (e.g., Brandt et al. 2019; Venner et al. 2021). Alternatively, many authors have fit the positions from the Hipparcos 2007 IAD directly in orbital analyses (e.g., Quirrenbach et al. 2011; Sahlmann et al. 2011; Snellen & Brown 2018; Feng et al. 2019; Nielsen et al. 2020; Lagrange et al. 2020). Future studies may include some of the 6617 sources. Without a correction of the data, the recovered proper motions can be systematically offset by a large fraction of the formal error. Such an offset would bias the inferred orbital parameters and companion masses. This risk can be mitigated by using htof with the built-in ad hoc correction.

The data corruption likewise has affected nearly the same subset of sources of the IAD on the Hipparcos 2007 DVD. In principle, the same ad hoc correction is possible. However, in practice it requires substantially more computation time because rejected transits (those marked with negative uncertainties in the Java tool) are not clearly indicated in the DVD IAD. Even the information about the number of rejected observations in the IAD header only gives the integer part of the percentage of rejected observations. This means that it is not clearly indicated if any source with less than 100 observations has zero or one rejected observation. We recommend that any work using the IAD from the Hipparcos 2007 DVD should exclude sources where the chi-squared partials of the data do not sum to zero. The DVD sources that htof failed to refit are given in htof/data/hip2_DVD_flagged.txt. We defined a refit failure as one with proper motion refit discrepancies exceeding 0.03 mas/yr. These stars also have significantly nonzero sums of $\chi^2$ partials. We encourage the reader to consider using the IAD corresponding to the Java tool, where htof has automatic correction built in and so these data are ready for a variety of use cases like orbit fitting.

5. Use Case I: Orbit Fitting

htof’s primary use case to date is in orbit fits that incorporate Gaia and Hipparcos absolute astrometry. htof is implemented in orvara (Brandt et al. 2021b), a Markov chain Monte Carlo (MCMC) code that employs the parallel-tempering sampler ptemcee (Foreman-Mackey et al. 2013; Vousden et al. 2016). htof is used to forward model the absolute astrometry within orvara, htof and orvara were used, for example, to infer a precise mass for Gl 229 B (Brandt et al. 2020; Brandt et al. 2021b), produce masses and orbital
parameters for two white dwarf companions (Bowler et al. 2021a), yield a dynamical mass estimate for a newly discovered brown dwarf companion to HD 33632 (Currie et al. 2020), infer the mass of a substellar companion to HD 47127 (Bowler et al. 2021b), produce refined masses and orbital parameters for β Pic b and c (Brandt et al. 2021a), derive the first dynamical mass for HR–8799–e (Brandt et al. 2021d), derive precise masses for six directly imaged brown dwarfs (Brandt et al. 2021b), and solve for masses (breaking the inclination degeneracy) of nine massive companions that previously had only RV detections (Li et al. 2021).

htof uses the Gaia scanning law, Hipparcos 1997, and 2007 IAD to forward model perturbations to the absolute astrometry due to companions. htof computes three proper motion perturbations per MCMC step: one for Gaia, one for Hipparcos, and finally one to the HGCA long-baseline proper motion. The unperturbed proper motions are cross calibrated and have already been placed in a common reference frame (Brandt 2018, 2021). htof’s forward modeling of the absolute astrometry is particularly relevant for sources where the precision on the mass of the companion is high. For Gl 229 B, with a mass measured to ≤1%, disabling htof’s exact forward modeling causes the inferred mass of the companion to shift by an amount comparable to its formal uncertainty (G. Brandt et al. 2021, submitted).

6. Use Case II: Astrometric Mission Forecasting

Precision astrometric missions can detect and characterize companions around stars by observing the reflex motion of the star in the plane of the sky due to its companion. Gaia expects to detect tens of thousands of substellar companions over its nominal 5 yr mission (Perryman et al. 2014). However, many additional missions have been proposed (in part) for exoplanet discovery and characterization. For example SIM and SIM Lite (which aimed at transiting planets), SIM and NGRST (which aimed at terrestrial planets) around any star. For NGRST, we use the 10 μas precision estimated by WFIRST Astrometry Working Group et al. (2019) for spatial scanning (single scan). Melchior et al. (2018) estimate a ~10 μas precision for bright stars from centering on diffraction spikes. The end-of-mission performance of Gaia on bright stars is expected to be a factor of a few better than it is in EDR3. The exact end-of-mission single-scan precision for Gaia is unavailable but we estimate it as follows. The Gaia collaboration predicts 10 μas parallax precision by Gaia DR4 for bright stars (3 < V < 12).19 The error on the sky-averaged position is 0.75× the parallax precision. Each source will be observed ~100 times. A rough estimate of the single-exposure precision is then ~10 × 0.75 = 7.5 μas. We inflate this slightly, to be conservative, to 12 μas.

We now consider which planets are detectable given three different combinations of data on β Pic: Gaia alone (which we label as Gaia), Gaia combined with Hipparcos (Gaia + HIP), and Gaia combined with a mock NGRST campaign (Gaia + NGRST). The mock NGRST campaign of β Pic consists of six randomly spaced NGRST spatial-scanning observations between 2025 and 2028. We assume a diagonal covariance matrix for each NGRST observation with 10 μas errors in R.A. and decl. The mock Gaia DR4 data are the 91 Gaia GOST observations planned for β Pic between 2014 and 2020. We assume equal AL errors of 120 μas and zero covariance between measurements. The Hipparcos data we use are the actual Hipparcos observations of β Pic from the 1997 reduction IAD.

We compute the Δχ² of a linear astrometric fit to the perturbed motion of β Pic for a swath of planetary masses and semimajor axes. For any given mass and semimajor axis, we assume a circular edge-on orbit (i = 90°) around β Pic A. We assume that effects like apparent acceleration from projected linear motion and timing fluctuations from light travel time have been accounted for. Finally, we take the average Δχ² across a uniform distribution of orbital phases. We define a body as detectable if it causes an astrometric perturbation on its host star with Δχ² > 30 in mass and semimajor axis space for β Pic and all three cases: Gaia, Gaia+NGRST, and Gaia+HIP. Hipparcos will be important for potential short-period planets in β Pic only if the Gaia end-of-mission parallax precision is substantially worse than 16 μas. In the Gaia+NGRST case (all blue regions), adding Hipparcos astrometry negligibly enlarges the detectable region because of the already long time baseline between Gaia and NGRST and the high precision of NGRST. β Pic c is detectable with confidence with Gaia DR4 alone (Δχ² > 400) and with extreme confidence (Δχ² > 1000) if combined with six NGRST observations. An unseen Saturn mass companion could be detected by combining Gaia and NGRST.

Lagrange et al. (2020) ruled out the presence of additional planets in the β Pic system more massive than ~2.5 M_Jup closer than 3 au; 3.5 M_Jup for planets whose semimajor axes are between 3 au and 7.5 au; and ~1–2 M_Jup for planets lying beyond 7.5 au. Figure 3 shows these limits as red lines. We find that a Gaia DR4 and Hipparcos merger could improve the limit between 3 au and 7.5 au to exclude additional planets (in edge-on orbits) more massive than 1.5 M_Jup. Adding six NGRST observations could exclude edge-on planets more massive than 0.2 M_Jup.

18 http://jasmine.nao.ac.jp/index-en.html and http://www.scholarpedia.org/article/JASMINE
19 https://www.cosmos.esa.int/web/gaia/science-performance
Figure 3. Mass and semimajor axis space for planets orbiting the star β Pic A in circular, edge-on orbits. Planets β Pic b and β Pic c have been placed according to their semimajor axes and masses (Brandt et al. 2021a). Solar system planets are shown for comparison. Blue regions indicate parameter space where a planet would be detectable with Δχ^2 > 30—corresponding to the Perszyk et al. (2014) detection criterion. Planets in any blue region (above the Gaia + NGRST contour) would be detectable by combining Gaia DR4 with six NGRST observations. Planets in the dark-blue region above the Gaia contour would be detectable by Gaia alone, and planets in either of the darkest two regions (Gaia or Gaia + HIP) could be discovered through a merging of the Gaia and Hipparcos IAD. The regions above the red lines correspond to additional planets ruled out by Lagrange et al. (2020). The code to reproduce the Gaia + NGRST contour is in the Jupyter examples notebook that accompanies htof.

7. Summary and Conclusions

We present htof, an open-source tool for using the Hipparcos and Gaia astrometry in a variety of applications. htof provides routines to parse and fit the IAD from both Hipparcos reductions and the Gaia scanning law. It is prepared for future Gaia data releases which will include the IAD and higher-order fits.

We suggest that 6617 sources within Hipparcos 2007 have corrupted IAD, and present htof’s ad hoc correction to this corruption (for the Java tool version of the IAD). htof can be used to forecast future astrometric missions. We find that Gaia DR4 merged with Hipparcos could improve the Lagrange et al. (2020) β Pic companion limits by a factor of 2, excluding additional planets more massive than ~1.5 M_Jup with semimajor axis’ between 3 au and 7.5 au. Jupiter and Saturn mass companions would be astrometrically detectable around β Pic if one combined Gaia DR4 with six NGRST observations.

htof is available at https://github.com/gmbrandt/htof and installable with pip install htof. The examples.ipynb Jupyter notebook provides examples of using htof. We welcome feedback and contributions.

We thank the referee for helpful feedback on this work. We thank Anthony G. A. Brown for helpful discussions about Gaia and Hipparcos, and for the sky path module in htof that we obtained, with permission, from the package astrometric-sky-path.20 We thank Floor van Leeuwen, for supporting us with access to the IAD from the Java tool, for helping us interpret the Java tool IAD and some of their detailed properties, and for helpful discussions of the manuscript. G.M.B. thanks Lachlan T. Lancaster for helpful discussions. D.M. gratefully acknowledges support from the European Space Agency (ESA) Research Fellow program. G.M.B. is supported by the National Science Foundation (NSF) Graduate Research Fellowship under grant no. 1650114. This work made use of the REBOUND code that is freely available at http://github.com/hannorein/rebound. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/Gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC; https://www.cosmos.esa.int/web/Gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. T.B. gratefully acknowledges support from NASA under grant #80NSSC18K0439.

Software: astropy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018), scipy (Virtanen et al. 2020), numpy (Oliphant 2006; van der Walt et al. 2011), pandas (McKinney 2010; Reback et al. 2021), Jupyter.

Appendix

The Ad Hoc Correction Algorithm

Here we detail the ad hoc correction algorithm for the Hipparcos 2007 Java tool IAD. The Jupyter notebook with the source code contains examples that demonstrate the ad hoc correction.

1. We separate the IAD into two blocks: the first five columns (orbit number, epoch, parallax factor, sine and cosine of the scan angle) into the left-hand side block L, and the last two columns (residuals and AL errors) into the right-hand side block R.
2. We assume that the last n residuals and (typically duplicate) AL errors are corrupted and therefore remove the last n rows from block R. This results in n too many rows in block L.
3. We iterate through all possible combinations of removing n rows from block L.21 For each iteration:
   (a) blocks L and R now have the same number of rows again. We recombine blocks L and R, yielding a modified IAD;
   (b) we calculate the quadrature sum of the chi-squared partials for this modified IAD.
4. We accept the modified IAD that gives the smallest quadrature sum of the chi-squared partials. This sum is typically less than 0.01.

ORCID iDs

G. Mirek Brandt orcid.org/0000-0003-0168-3010
Daniel Michalik orcid.org/0000-0002-7618-6556
Timothy D. Brandt orcid.org/0000-0003-2630-8073
Yiting Li orcid.org/0000-0002-6845-9702
Trent J. Dupuy orcid.org/0000-0001-9823-1445

21 We speed up the algorithm for the 180 sources with n > 5. These have a large number of combinatoric possibilities. Often, one orbit contains multiple observations. These often almost have identical epochs and scan angles. For all practical purposes, we find that it does not matter which one of the observations within one orbit we remove, as long as we remove the correct number of observations from that orbit.

20 https://github.com/agabrown/astrometric-sky-path
