Icarus 245 (2015) 94–111

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Star catalog position and proper motion corrections in asteroid astrometry

D. Farnocchia [a,*], S.R. Chesley [a], A.B. Chamberlin [a], D.J. Tholen [b]

[a] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[b] Institute for Astronomy, University of Hawaii, Honolulu, HI 96822, USA

ARTICLE INFO

Article history:
Received 20 June 2014
Revised 28 July 2014
Accepted 30 July 2014
Available online 28 September 2014

Keywords:
Asteroids
Orbit determination
Astrometry

ABSTRACT

We provide a scheme to correct asteroid astrometric observations for star catalog systematic errors due to inaccurate star positions and proper motions. As reference we select the most accurate stars in the PPMXL catalog, i.e., those based on 2MASS astrometry. We compute position and proper motion corrections for 19 of the most used star catalogs. The use of these corrections provides better ephemeris predictions and improves the error statistics of astrometric observations, e.g., by removing most of the regional systematic errors previously seen in Pan-STARRS PS1 asteroid astrometry. The correction table is publicly available at ftp://ssd.jpl.nasa.gov/pub/ssd/debias/debias_2014.tgz and can be freely used in orbit determination algorithms to obtain more reliable asteroid trajectories.

1. Introduction

Whenever we compute an asteroid's orbit, it comes with an uncertainty region due to the limited accuracy of the available observations. In other words, orbits are only known in a statistical sense and the accuracy of the related probabilistic interpretation relies heavily on the observation accuracy and error modeling. Therefore, it is important to apply an appropriate statistical treatment to the observations used to compute the orbit.

The vast majority of asteroid astrometry is given by optical observations, i.e., each observation provides two angular measurements, typically right ascension (RA) and declination (DEC) in the equatorial reference frame J2000, describing the position of an asteroid on the celestial sphere at a specified time. Such measurements are obtained with respect to nearby reference stars, whose positions are provided by a reference star catalog. In general, the more accurate the star catalog, the more accurate the observation.

Despite the common assumption that observation errors have zero mean, Carpino et al. (2003) show that asteroid astrometry is significantly biased and suggest the reason is the presence of systematic errors in the star catalogs used to reduce the astrometry.

Chesley et al. (2010) computed star catalog systematic errors for USNO-A1.0 (Monet, 1996), USNO-A2.0 (Monet, 1998), USNO-B1.0 (Monet et al., 2003), UCAC2 (Zacharias et al., 2004b), and Tycho-2 (Høg et al., 2000) by comparing each of these catalogs to 2MASS (Skrutskie et al., 2006). Despite the lack of proper motions, 2MASS was chosen as the reference catalog because of its very accurate star positions at epoch J2000.0 and high spatial density. Chesley et al. (2010) showed that correcting asteroid astrometry using their computed biases leads to significantly lower systematic errors and statistically better ephemeris predictions.

Pan-STARRS PS1 (Hodapp et al., 2004) is one of the most accurate asteroid surveys with an astrometric quality of the order of 0.1″. Although this survey uses 2MASS as reference catalog for the astrometric reduction, Milani et al. (2012) found that Pan-STARRS PS1 data have surprisingly high biases on the order of 0.05–0.1″ with a strong regional dependence. Tholen et al. (2013b) show that the lack of proper motion in 2MASS is likely to be the cause of the Pan-STARRS PS1 astrometry systematic errors and signatures. Moreover, they suggest that PPMXL (Roeser et al., 2010) be used as reference catalog because of its spatial density, accuracy comparable to that of 2MASS, and availability of proper motion information.

Since the lack of proper motion can be significant for high quality observations, in this paper we describe how to correct asteroid observations for both position and proper motion errors. Moreover, we perform this analysis for a more comprehensive list of star catalogs than that considered in Chesley et al. (2010).

2. Asteroid astrometry

As of January 2014 more than 600,000 asteroids have been designated, ~60% of which are numbered. The number of asteroid optical observations is already larger than 100,000,000 and increases every day. Observers submit their observations to the

* Corresponding author.
E-mail address: Davide.Farnocchia@jpl.nasa.gov (D. Farnocchia).

http://dx.doi.org/10.1016/j.icarus.2014.07.033
0019-1035/

Table 1
Star catalogs and MPC flags. The number of asteroid observations for each catalog account for all the astrometry available up to January 7, 2014.

Catalog	MPC flag	Number of stars	Asteroid observations		Reference
			Count	%	
USNO-A2.0	c	526,280,881	40,408,360	38.47	Monet (1998)
UCAC-2	r	48,330,571	29,793,925	28.37	Zacharias et al. (2004b)
USNO-B1.0	o	1,045,175,762	12,834,999	12.22	Monet et al. (2003)
2MASS	L	470,992,970	8,136,250	7.75	Skrutskie et al. (2006)
UCAC-4	q	113,780,093	2,629,456	2.50	Zacharias et al. (2013)
UCAC-3	u	100,766,420	2,228,325	2.12	Zacharias et al. (2010)
USNO-A1.0	a	488,006,860	2,193,938	2.08	Monet (1996)
USNO-SA2.0	d	55,368,239	1,698,129	1.62	Monet (1998)
GSC-1.1	i	18,836,912	614,617	0.59	Lasker et al. (1996)
UCAC-1	e	27,425,433	501,774	0.48	Zacharias et al. (2000)
SDSS-DR7	N	357,175,411	479,914	0.46	Abazajian et al. (2009)
GSC-ACT	m	18,836,912	404,473	0.39	Lasker et al. (1999)
CMC-14	w	95,858,475	361,928	0.34	Copenhagen University et al. (2006)
Tycho-2	g	2,430,468	355,813	0.34	Høg et al. (2000)
USNO-SA1.0	b	54,787,624	337,561	0.32	Monet (1996)
GSC (unspecified)	z	N/A	288,156	0.27	N/A
ACT	l	988,758	117,638	0.11	Urban et al. (1998)
PPMXL	t	910,468,688	88,328	0.08	Roeser et al. (2010)
NOMAD	v	1,117,612,732	58,266	0.06	Zacharias et al. (2004a)
PPM	p	378,910	41,468	0.04	Roeser and Bastian (1991)
GSC-1.2	j	18,841,548	16,975	0.02	Morrison et al. (2001)

Minor Planet Center (MPC)[1] and usually provide information on the catalog used to perform the astrometric reduction. The MPC in turn makes the catalog information publicly available by using an alphabetical flag.[2]

Table 1 shows the MPC flag, the number of stars, and the number of asteroid observations for different catalogs. We only consider the catalogs for which the number of asteroid observations reported to the MPC with the corresponding catalog flag was larger than 40,000 as of January 2014. We also included the GSC-1.2 (Morrison et al., 2001) catalog to complete the GSC-1 catalog series. The most used catalog is USNO-A2.0, with more than 40,000,000 asteroid observations. 2MASS, which was used as the reference catalog by Chesley et al. (2010), is the fourth most used catalog and the related astrometry is dominated by Pan-STARRS PS1 observations (more than 75% of the sample). Observations reported with code 'z' were reduced with one of the GSC catalogs, but we do not know which one.

3. Star catalog position and proper motion corrections

To correct asteroid optical astrometry for star catalog systematic errors, we need to select a reference for comparison with the other catalogs. Such a selection is far from easy. Hipparcos (Perryman et al., 1997) and Tycho2 are space-based, so they are not subject to differential refraction corrections as ground-based observations are, possibly making them the best available catalogs. However, a reference catalog should be both dense and accurate and neither Tycho-2 nor Hipparcos are dense enough. As shown in Table 1, the catalogs with the largest number of stars include USNO-A1.0 (Monet, 1996), USNO-A2.0 (Monet, 1998), USNO-B1.0 (Monet et al., 2003), 2MASS (Skrutskie et al., 2006), PPMXL (Roeser et al., 2010), and NOMAD (Zacharias et al., 2004a). Chesley et al. (2010) proved that the USNO catalogs are affected by systematic errors in position as large as 1–2″. NOMAD is a simple merge of the Hipparcos, Tycho-2, UCAC2, and USNO-B1.0 and is therefore still affected by the biases present in USNO-B1.0. Tholen et al. (2013b) show that 2MASS is not the appropriate choice because of the lack of proper motion. PPMXL (Roeser et al., 2010) is also a merge of 2MASS and USNO-B1.0, but it includes proper motions and a critical reprocessing of star positions from 2MASS and USNO-B1.0. Therefore, PPXML seems a sensible choice for a reference catalog. However, tests similar to one presented in Section 4.3 were not satisfactory as we found that correcting with respect to PPMXL rather than 2MASS (as in Chesley et al., 2010) can provide less accurate predictions. As described by Roeser et al. (2010), more than 50% of PPMXL stars are based on USNO-B1.0 and are not accurate enough for our purposes. To fix this problem, we selected as a reference catalog the subset of PPMXL corresponding to over 400 millions stars derived from 2MASS. This reference benefits from the accuracy of 2MASS star positions and yet accounts for proper motions.

As in Chesley et al. (2010), to compare the different star catalogs to our reference catalog we divided the celestial sphere into 49,152 equal-area tiles ($\sim$0.8 deg^2) using the JPL HEALPix package (Górski et al., 2005). For all the catalogs analyzed, we took star positions at epoch J2000.0. To identify stars in common within a given tile we used a spatial correlation of 2″. Whenever more than one identification with the same star is possible, we need to be careful and avoid spurious identifications. If $d_i, i = 1, N$ are the distances between the considered star and the matches in the reference catalog, as a safety measure we selected the identification j only if $d_j < 0.2 d_i$ for $i = 1, N$ and $i \neq j$. If none of the identifications met this condition we rejected all the identification to avoid including spurious matches in our analysis.

We also made sure that stars in the reference catalog were not paired to more than one star. For each tile we computed the average correction in position and proper motion for both right ascension and declination. Because of the present biases, for some catalogs the 2″ spatial correlation may not be enough to find matching stars. Therefore, we applied the procedure iteratively, i.e., we corrected the stars in the catalog to be debiased by subtracting the systematic error for the corresponding tile found at the previous iteration.

At the end of the process, for each given tile and catalog we have a correction in RA and DEC at epoch J2000.0, (ΔRA_{2000}, ΔDEC_{2000}), and proper motion corrections ($\Delta\mu_{RA}, \Delta\mu_{DEC}$). These numbers can be used to correct asteroid astrometric observations by subtracting the following quantities:

$$\Delta RA = \Delta RA_{2000} + \Delta\mu_{RA}(t - 2000.0)$$
$$\Delta DEC = \Delta DEC_{2000} + \Delta\mu_{DEC}(t - 2000.0)$$

[1] http://www.minorplanetcenter.net/.
[2] http://www.minorplanetcenter.net/iau/info/CatalogueCodes.html.