A Giant Step: from Milli- to Micro-arcsecond Astrometry
Proceedings IAU Symposium No. 248, 2007
W. J. Jin, I. Platais & M. A. C. Perryman, eds.

doi:10.1017/S174392130801942X

Maintenance and densification: current proper-motion catalogs

T. M. Girard

Department of Astronomy, Yale University,
P.O. Box 208101, New Haven, Connecticut, 06520-8101, USA
email: girard@astro.yale.edu

Abstract. An overview of currently available, large-area, proper-motion catalogs is presented. These include the well-known catalogs based on historical Schmidt-telescope surveys as well as other projects that make use of observational material the primary purpose of which, from inception, was the determination of proper motions. The various catalogs are characterized and compared, with an emphasis on their limitations and their appropriateness for various astrophysical uses.

In addition to allowing for the maintenance of a practical celestial reference system, absolute proper-motion surveys provide the raw material from which a better understanding of our Galaxy's structure and kinematics can be built. Several examples will be cited in which large proper-motion surveys are used to probe and describe the distinct stellar components that comprise our Milky Way Galaxy.

Keywords. catalogs, astrometry

1. Introduction

Proper-motion measures perform the glamourless, utilitarian function of maintaining positional reference catalogs into the future. Beyond this obvious and important role they also provide more direct astrophysical functions. Among these are their use as a distance/luminosity estimator, thus providing a means of discrimination between classes of stellar objects, (e.g. via reduced proper motions). An even more direct astrophysical use of proper-motion measures is in the construction of transverse velocity distributions, a key tool in the study of the kinematics and equilibrium structure of the various Galactic components, (i.e., thin disk, thick disk, and halo).

Not all proper-motion catalogs are designed to accomplish each of the functions mentioned above. It is important to select the appropriate proper-motion catalog for the proper-motion task at hand. This may appear obvious, but the literature is littered with studies that have misused available proper-motion catalogs, overstretching their limits, by mistaking precision for accuracy or assuming $\sqrt{N}$ can lead to perfection.

It is thus the purpose of this paper to give an overview of *some* of the currently available proper-motion catalogs and their approximate characteristics such that non-astrometrists can choose and use them wisely. The following section lists and describes the most oft-used as well as some lesser-known proper-motion catalogs. In each of the subsequent sections examples are given of particular catalogs appropriate to the three tasks mentioned earlier; *i)* reference frame utility, *ii)* stellar distance estimation and luminosity class discrimination, and *iii)* kinematic study of Galactic components.

Table 1. *Some* Currently available proper-motion catalogs

#. Catalog	N	Coverage	Dens	V_{comp}	σ_μ (r/a)	Source Material/Notes
"The Big Three"						
01. Hipparcos	118K	all-sky	3	7.5	0.9 / 0.25	fully satellite-based
02. Tycho-2	2.5M	all-sky	62	11.5	2.5/ ?	Hipp. starmapper + grnd-based cats
03. UCAC2	48M	$\delta < +45°$	1.6K	16.5	$\sim$3/ $\sim$3	recent CCD + grnd-based cats
Schmidt survey-based						
#. Catalog	**N**	**Coverage**	**Dens**	**V_{comp}**	**σ_μ (r/a)**	**Source Material/Notes**
04. USNO-B1.0	1046M	all-sky	25K	$\sim$ 21	$\sim$5/ -	POSS1, POSS2, ESO, AAO, SERC
05. GSC 2.3	945M	all-sky	23K	$\sim$ 21	?? ?	POSS1, POSS2, ESO, AAo, SERC
06. SuperCOSMOS	>1000M	$\delta < +3°$	46K	$\sim$ 21	10-50/ <1 (?)	POSS1, POSS2, UKST, ESO
Schmidt-derivative						
#. Catalog	**N**	**Coverage**	**Dens**	**V_{comp}**	**σ_μ (r/a)**	**Source Material/Notes**
07. SDSS-USNOB1	$\sim$8M	2K sq deg	3.8K	19.7	3-3.5/ <0.5(?)	SDSS minus USNOB1
Proper-motion threshold						
#. Catalog	**N**	**Coverage**	**Dens**	**V_{comp}**	**σ_μ (r/a)**	**Source Material/Notes**
08. rNLTT	59K	44% sky	3	$\sim$ 18	3-5/	NLTT+POSS1+2MASS
09. LSPM	122K	[all-sky]	3	21	$\sim$5/	DSS's and SUPERBLINK software $\mu > 150$ mas/yr
Rank-merged						
#. Catalog	**N**	**Coverage**	**Dens**	**V_{comp}**	**σ_μ (r/a)**	**Source Material/Notes**
10. NOMAD	1100M	all-sky	27K	$\sim$ 21	1-5/ 0.2 - ?	Hipp.+Tycho2+UCAC2+USNOB1
Astrograph-based proper-motion surveys						
#. Catalog	**N**	**Coverage**	**Dens**	**V_{comp}**	**σ_μ (r/a)**	**Source Material/Notes**
11. NPM	0.4M	$\delta > -23°$	13	—	$\sim$5/ $\sim$1	astrograph w/ obj. grating
12. SPM	11M	$-30°$ band (3700 sq°)	2.9K	17.5	3-5/ 0.4	astrograph w/ obj. grating
CdC-based						
#. Catalog	**N**	**Coverage**	**Dens**	**V_{comp}**	**σ_μ (r/a)**	**Source Material/Notes**
13. PM2000	2.7M	$+15°$ band	0.5K	15.4	TBD	Bordeaux Meridian Circle (M2000) +CdC+AC2000+USNOA2+YS3
14. CdC-SF1	0.5M	$-6°$ band (1080 sq°)	0.5K	15.1	1.1-3/ ?	San Fernando CdC + UCAC2 (commercial flatbed scanner)

01. ESA 1997, (ESA SP-1200) (Noordwijk: ESA)
02. Høg *et al.* 2000, AA 355, 27
03. Zacharias, *et al.* 2004, AJ 127, 3043
04. Monet *et al.* 2003, AJ 125, 984
05. Spagna *et al.* 2006, Mem. S. A. It. 77, 1166 (see also Bucciarelli in these proceedings)
06. Hambly *et al.* 2001, MNRAS 326, 1315
07. Munn *et al.* 2004, AJ 127, 3034
08. Salim & Gould 2003, ApJ 582, 1011
09. Lépine & Shara 2005, AJ 129, 1483 (see also Lépine in these proceedings)
10. Zacharias *et al.* 2004, AAS 205.4815
11. Hanson *et al.* 2004, AJ 128, 1430
12. Girard *et al.* 2004, AJ 127, 3060
13. Ducourant *et al.* 2006, AA 448, 1235
14. Vicente *et al.* 2007, AA 471, 1077

https://doi.org/10.1017/S174392130801942X Published online by Cambridge University Press

2. Proper-motion catalogs

Table 1 lists some of the more useful proper-motion catalogs currently available to the astronomy community. The catalogs have been divided into groups in a somewhat arbitrary fashion, primarily by source material, although three catalogs have been singled out as being the most often used and (generally) rightly so. The columns of the table list the catalog name; the number of objects it contains; the sky coverage; the density in objects per square degree; a rough estimate of the V-band completeness limit if it has one; the estimated proper-motion uncertainty per star (in mas/yr) both in a relative sense (r) and in an absolute sense (a), that is the limit of the proper-motion system of the catalog and thus the "floor" one should expect when considering ensembles of stars; and finally a description of the source material from which the catalog was constructed and/or other notes. References for the catalogs are given in the tablenotes.

The Hipparcos and Tycho-2 catalogs need no introduction. These are superb resources in general as well as specifically with respect to their proper motions. Although ostensibly on the system of the ICRS via Hipparcos, the uncertainty of the absolute proper-motion system of Tycho-2, particularly at the faint end, is not well-established due to the use of early-epoch ground-based plate catalogs and the everpresent question of residual magnitude equation, as discussed in Section 5. The UCAC2, with its density of 1600 stars per square degree, is an extremely useful astrometric reference. In its current version its proper motions suffer from systematics that are on the order of 3 mas/yr. Addressing this, as well as issues of completeness and the inclusion of the north celestial cap, will be major improvements in the next UCAC release expected in 2008.

Among the catalog products of the major Schmidt-survey plate digitization programs, the USNO-B1 is probably the most often used. Its proper motions are not absolute. More precise and accurate are the proper motions derived from the USNO-B1 in combination with other databases, such as the Sloan Digital Sky Survey.

Some other catalogs worthy of mention are those specifically geared to find stars with high proper motions, above some cutoff threshold. Naturally, these are most useful in studies seeking to detect nearby stars. Examples of such studies are mentioned briefly in Section 4.

NOMAD is a simple rank merging of existing astrometric catalogs. The proper-motion systems of the various sources should not be expected to be homogeneous. On the other hand, absolute proper motions on an absolute frame were the design goal of the NPM and SPM programs. The NPM, however, is not complete to any magnitude, measuring just a fraction of the stars on the plates due to time constraints. The most recent catalog of the SPM program, the SPM3, is nominally complete to V=17.5.

Finally, there are recent proper-motion programs that attempt to exploit the largely neglected turn-of-the-century Carte du Ciel plates. The San Fernando project being noteworthy for its successful use of a commercial flatbed scanner in digitizing the original plate material.

3. Utilitarian use

Perhaps the most common use of astrometric catalogs is as a reference system upon which to express the celestial coordinates of a target or targets of interest. This may, for example, be to facilitate cross-identification by position, to provide input coordinates for follow-up fiber-optic spectroscopic observations, or to calibrate the optical field angle distortion of a new telescope and/or instrument, (the last being the most demanding of these examples). In these cases the most important aspects of the reference catalog to consider are its precision at epoch and whether or not the catalog provides a sufficient number of stars that are in a measurable magnitude range. The proper motions serve the purpose of lessening the degradation of positional precision at the epoch of interest.

Figure 1 illustrates the tradeoff between precision at a recent epoch and magnitude of available reference stars, which of course is related to the density of reference stars (see Table 1) for the most commonly used astrometric reference catalogs. These include "the big three" along with the USNO-B1, (which one might consider the "the big fourth"), and the 2MASS point source catalog (Skrutskie *et al.* 2006). While lacking proper motions and not originally intended as an astrometric catalog, 2MASS can provide a dense set of reference stars at a modern epoch. The utility of 2MASS and the USNO-B1 cannot be overestimated for cases when deep and dense astrometric reference fields are needed.

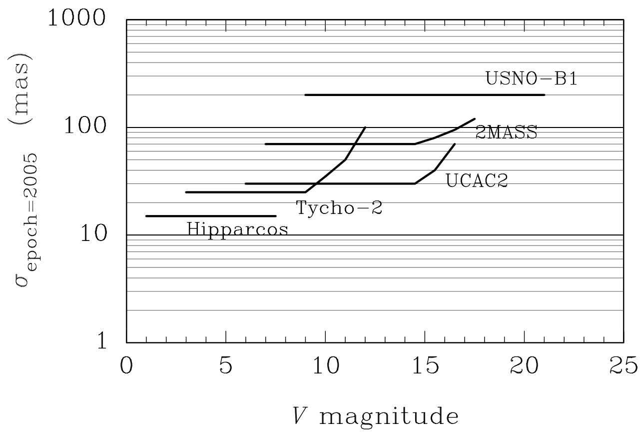

Figure 1. A comparison of useful astrometric catalogs. Approximate positional uncertainties at epoch 2005 are shown schematically as a function of magnitude.

4. Distance/luminosity estimation

Proper motions can provide a practical estimate of distance, in a statistical sense. A clever use of proper motions in this regard is to separate a sample of stars into known luminosity classes by means of the reduced proper motion. The reduced proper motion is a proxy of sorts for absolute magnitude given by the following expression,

$$H_V = V + 5log\mu + 5,$$

where V is the apparent magnitude in some passband (e.g. Johnson V) and μ is the total proper motion in arcsec/yr. The technique relies on stars in a sample sharing a common and relatively narrow tangential velocity distribution and the simple relation between tangential velocity and proper motion, i.e. the ratio of these being proportional to distance. In practice the technique works because of the large range in stellar luminosities and distances relative to their variation in velocities. In particular, the reduced proper motion diagram, in which H is plotted versus a color index, can provide an excellent discriminant of luminosity class, especially for nearby star samples.

A reduced proper motion diagram, taken from Finch *et al.* (2007), is reproduced in the left panel of Figure 2. White dwarf candidates are separated nicely from main sequence stars in this manner using proper motions derived from multiple epochs of Schmidt survey plate scans and software developed as part of the SuperCOSMOS-RECONS project, (Henry *et al.* 2004). An example of the astrophysical knowledge that can be gleaned from

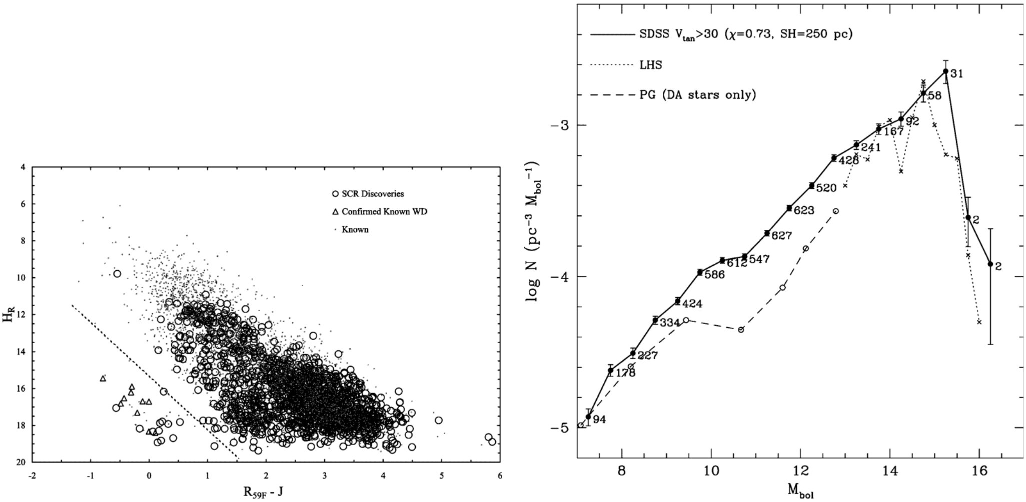

Figure 2. Examples of the use of reduced proper motions. *Left:* This reduced proper-motion diagram of Finch *et al.* (2007, their Fg. 5) was constructed using their SuperCOSMOS-RECONS proper-motion determinations. The white dwarfs are well separated from main-sequence dwarfs. *Right:* In a similar study, the white-dwarf luminosity function determined by Harris *et al.* (2006, their Fig. 4) was based on reduced-proper-motion selection using SDSS-USNOB1 proper motions.

this type of investigation is given in the right panel of Figure 2. It shows the white-dwarf luminosity function based on a similar study that made use of proper motions derived from SDSS-USNOB1, (see Harris *et al.* 2006). In this and the Finch *et al.* study a deep sample of precise proper motions is the key to success. Accuracy of the proper-motion system is not critical.

5. Kinematic description of Galactic components

Both precision and accuracy of a proper-motion catalog are important in studies of Galactic kinematics. As an example, the Yale/San Juan Southern Proper Motion (SPM) program, the southern-sky counterpart to the Lick NPM program, was designed from inception to yield precise and accurate proper motions over a wide magnitude range. These photographic surveys relied on an objective grating and two separate exposures per field to not only increase the effective dynamic range of the plates but also to provide a means of correcting for the bane of the photographic astrometrist - magnitude equation. Magnitude equation is the term given to the magnitude-dependent bias in image centers that is caused by the combination of non-linear detector and asymmetric image profiles. It is present to some degree in virtually all photographic measures and, to a generally lesser extent, in CCD positions as well. As demonstrated by Girard *et al.* (1998), the grating images on the SPM plates allow a self-calibration for magnitude equation to be bootstrapped from each plate and an individual correction applied.

Using SPM3 proper motions and 2MASS J, K photometry, Girard *et al.* (2006) isolated a sample of thick-disk giants at the South Galactic Pole (SGP) in order to ascertain the kinematical nature of the Galactic thick disk. Distances were estimated photometrically from the 2MASS photometry in a Monte Carlo fashion that automatically incorporated and modelled the Malmquist and Lutz-Kelker type biases. (See Girard *et al.* 2006 for details.)

The resulting *observed* thick-disk velocity distributions are shown in Figure 3. The Monte-Carlo modeling allows us to infer the *intrinsic* distributions, assuming the

https://doi.org/10.1017/S174392130801942X Published online by Cambridge University Press

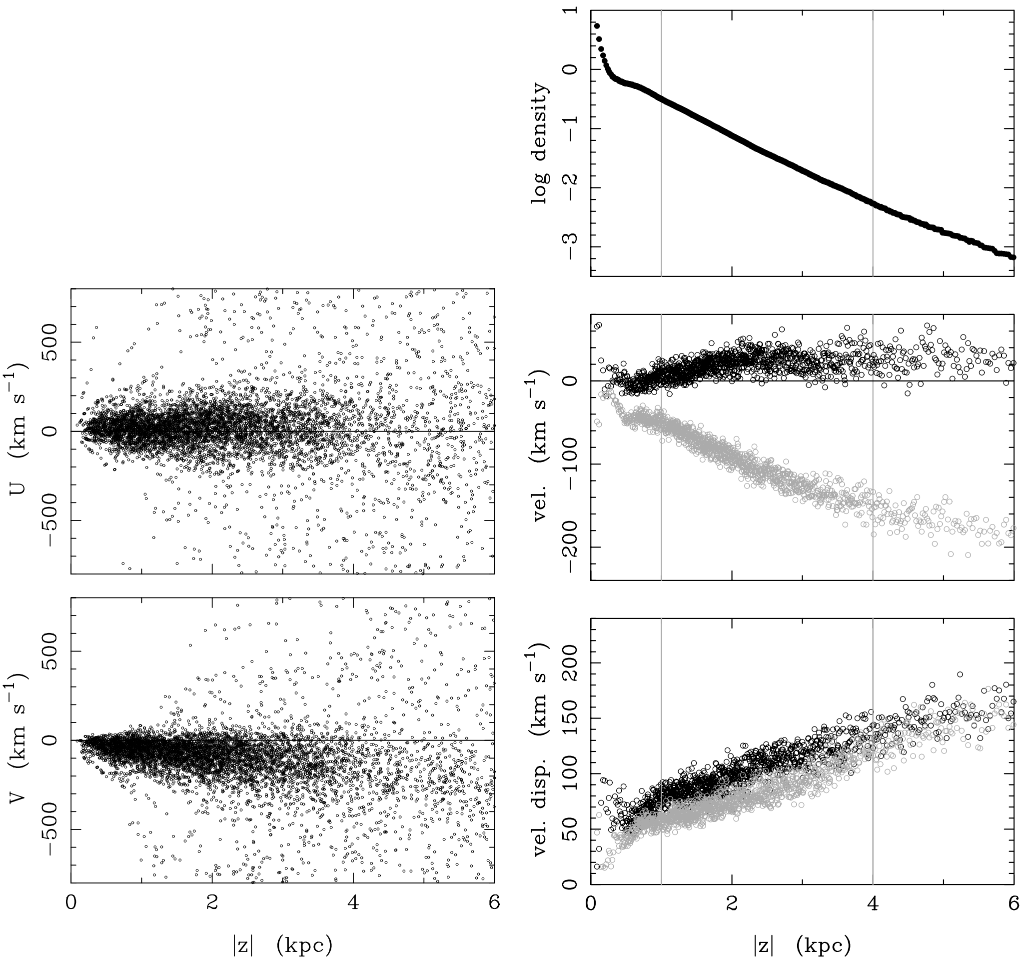

Figure 3. Transverse velocity distributions, as derived from SPM3 proper motions, for a predominantly thick-disk sample of ~ 1100 giants at the SGP. *Left:* U,V velocities and distances are estimated in a Monte-Carlo fashion, integrating over an assumed absolute magnitude distribution. Dwarf stars, incorrectly classified as giants, are easily identified by their unrealistically high velocities. *Right:* Observed number density, transverse velocity, and velocity dispersion profiles as a function of distance for this sample. In the lower two panels black symbols illustrate the U profiles while gray symbols signify the V profiles. The sample is considered well-measured in the range 1 to 4 kpc.

proper-motion errors are well-understood. Notably, we derive a scale height for the thick disk of 783 ± 48 pc; a vertical gradient to the V velocity (shear) of -30 ± 3 km/s/kpc; and a vertical gradient for the velocity dispersions in both the U and V components of $\sim 9 \pm 3$ km/s/kpc. It is possible to show that for reasonable assumptions as to the form of the Galactic potential, the slight gradient in σ_U is consistent with the large gradient in V within a condition of dynamical equilibrium.

6. Conclusion

"The right tool for the job," is an expression familiar to weekend handymen and professionals alike. The present paper has attempted to stress the importance of utilizing the appropriate proper-motion catalog for the task at hand. A listing of some of the more useful such catalogs has been provided, as have several examples of fruitful science that results when proper-motion measures are properly considered and used. For diplomatic purposes, it was thought best not to include here examples of the *improper* use of proper-motion data. The reader is warned, however, that the literature is not without such occurences.

One minor instance, drawn from personal experience and involving an anonymous reviewer of a research proposal for which this author was a co-investigator, will perhaps make the point. It was stated by the reviewer that it was wasteful to fund a project seeking to measure and use, for Galactic kinematic studies, absolute proper motions down to V=17.5 based on a specially designed program to determine such (i.e. the SPM) when the USNO-B1 catalog already gives proper motions to a similar precision and to a deeper magnitude limit. Figure 4 illustrates the folly of this statement. The USNO-B1 is a tremendous resource with a multitude of important uses but it is not the appropriate tool to use to discern the detailed nature of Milky Way kinematics. The following year the research proposal was resubmitted with the new inclusion of Figure 4. It can be happily reported that the proposal was accepted and funded, leading to the completion of the SPM observing program and the soon-to-be-released SPM4 southern-sky proper-motion catalog.

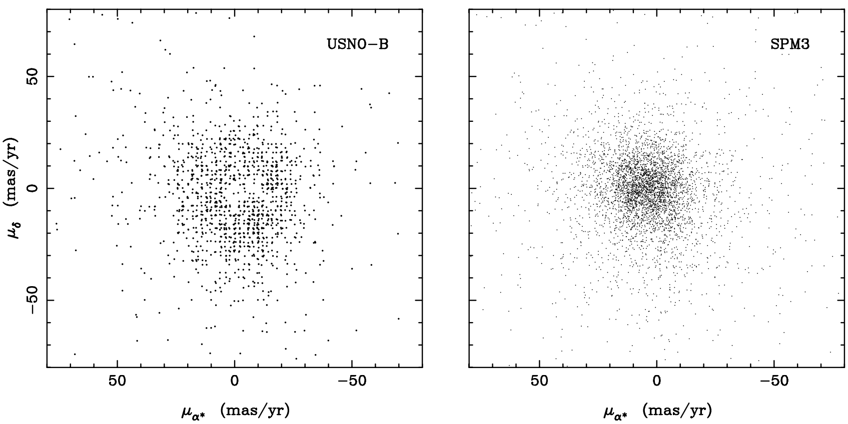

Figure 4. The central 2° × 2° region of an arbitrary southern-sky SPM field. The vector point diagram constructed using proper motions from the USNO-B1 *(left panel)* is compared to that of the SPM3 *(right panel)* for stars in common.

References

Finch, C. T., Henry, T. J., Subasavage, J. P., Jao, W.-C., & Hambly, N. C. 2007, *AJ*, 133, 2898

Girard, T. M., Korchagin, V. I., Casetti-Dinescu, D. I., van Altena, W. F., López, C. E., & Monet, D. G. 2006, *AJ*, 132, 1768

Girard, T. M., Platais, I., Kozhurina-Platais, V., van Altena, W. F., & López 1998, *AJ*, 115, 855

Harris, H. C., Munn, J. A., Kilic, M., Liebert, J., Williams, K. A., von Hippel, T., Levine, S. E., Monet, D. G., & 11 coauthors 2006, *AJ*, 131, 571

Henry, T. J., Subasavage, J. P., Brown, M. A., Beaulieu, T. D., Jao, W.-C., & Hambly, N. C. 2004, *AJ*, 128, 2460

Skrutskie, M. F., Cutri, R. M., Stiening, R., Weinberg, M. D., Schneider, S., & 26 coauthors 2006, *AJ*, 131, 1163

https://doi.org/10.1017/S174392130801942X Published online by Cambridge University Press