A Giant Step: from Milli- to Micro-arcsecond Astrometry
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The extended solar neighborhood: precision astrometry from the Pan-STARRS 1 3π Survey

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Abstract. The Pan-STARRS pathfinding telescope PS1 will begin a major set of surveys starting in 2008, and lasting for 3.5 years. One of these, the PS1 3π Survey, will repeatedly observe the entire sky north of -30 degrees, visiting every position 12 times in each of 5 filters. With single-epoch astrometry of 10 milliarcseconds, these observations will yield parallaxes for stars within 100 pc and proper motions out to several hundred pc. The result will be an unprecedented view on nearby stellar populations and insight into the dynamical structure of the local portions of the Galaxy. One exciting science product will be a volume-limited sample of nearby low-mass objects including thousands of L dwarfs, hundreds of T dwarfs, and perhaps even cooler sub-stellar objects. Another project will use proper-motion measurements to improve the membership of nearby star forming regions.

Keywords. astrometry, surveys, stars: low-mass, brown dwarfs, stars: formation

1. The Pan-STARRS project & PS1

The Pan-STARRS project, led by the University of Hawaii, is developing a unique optical survey instrument (PS4) consisting of four co-aligned wide-field telescopes. Each telescope has a 1.8 m diameter primary mirror and a 7 degree^2 field-of-view, imaged with a well-sampled 1.4 Gigapixel camera. This instrument is planned to be completed on Mauna Kea in the 2010 timeframe. As a pathfinder for the PS4 system, the Pan-STARRS project has built a single telescope system (PS1) on the summit of Haleakala on the Hawaiian island of Maui, consisting of a full-scale version of one of the PS4 telescope systems.

PS1 was originally envisioned as a test-bed for the commissioning, testing, and calibration of the Pan-STARRS hardware and software in anticipation of the full Pan-STARRS 4 telescope array. Recognizing the excellent survey capabilities of the PS1 Telescope, the Pan-STARRS project has made the science survey from PS1 a priority, and has formed the PS1 Science Consortium to guide the science observations and extract the scientific results from this telescope. Joining the University of Hawaii Institute for Astronomy in the PS1SC are the Max Planck Institute for Astronomy, the Max Plank Institute for Extraterrestrial Physics, the Johns Hopkins University, University of Durham, University of Edinburgh, Queen's University Belfast, the Harvard-Smithsonian Center for Astrophysics, and the Las Cumbres Observatory Global Telescope.

2. The surveys & the PS1 3π survey

The baseline PS1 survey plan consists of several science surveys, each with a trade off between coverage area and frequency (and/or depth) of observations. Three PS1 survey programs will perform repeated observations of a total of 14 fields, with science goals of detecting supernovae, planetary transits, and for one field, microlensing and variables in M31. One survey program will observe the sky in the direction of the Earth's orbit to detect near Earth asteroids. The majority of the available time (56%) will be dedicated to the PS1 3π Survey, a multi-epoch, multi-filter survey of the observable sky from Haleakala, roughly the 3π steradians north of -30 degrees Declination. Many science projects will make use of this survey, and the survey parameters have been carefully chosen to optimize between these different goals. These science goals include a survey of the Solar System (which motivates much of the timing), an examination of the local solar neighborhood (which motivates the large time-baseline observations and use of the reddest filters), and a large-scale galaxy and weak-lensing survey (which motivates the depth and color choices). The PS1 Survey Mission is expected to run for 3.5 years, starting soon after the telescope is commissioned in early-2008.

The PS1 3π Survey will be a major advance in several respects over existing large-scale surveys. The depth in a single visit will equal or exceed the Sloan Digital Sky Survey with the added dimension of multi-epoch observations. Each field will be observed 12 times in each of the 5 stellar filters ($grizy$), with a 5σ detection limit in the range 20.6–23.2 depending on the filter (see Table 1). The survey cadence is designed to enhance the detection of high-proper motion stars and the measurement of the trignometric parallaxes. A given field is observed 20 times within the course of a year, with observations distributed to enhance the detection of the parallax. The gri filters, which are most sensitive to the solar system objects, will be observed within the 3 months surrounding opposition, i.e., observed near the meridian within 2 hours of midnight. The reddest filters (zy), which are most sensitive to the low-mass stars and substellar objects of primary interest in the local solar neighborhood, will be used to observe fields between 70 and 90 degrees from opposition. These are observed near the meridian in the hours after sunrise and before sunset, and thus maximize the parallax factor for these fields.

3. Astrometry expectations

The goals of the PS1 survey include relative astrometry with an error floor of 10 milliarcseconds. These values are consistent with our measurements from data taken at other sites, combined with the seeing expectations for Haleakala. We have used a variety of test data to evaluate the analysis process and to test the accuracy achieved in similar systems and circumstances. A major component of the test data consists of observations from the CFHT MegaPrime 1 square degree camera, which approaches the PS1 Gigapixel Camera in scale.

Table 1. Predicted PS1 zero-points, sky brightness, magnitude limits.

filter	λ (nm)	$\Delta\lambda$ (nm)	m_0 (mag)	μ (mag asec^{-2})	Magnitude at S/N 100	25	5
g	480	128	24.9	21.9	20.0	21.4	23.2
r	620	137	25.1	20.9	19.4	20.9	22.7
i	750	126	25.0	20.1	19.4	20.9	22.6
z	870	102	24.6	19.3	18.4	19.9	21.6
y	990	57	23.0	18.0	17.0	18.4	20.1

The astrometric analysis of data from a large-scale mosaic camera offers interesting challenges, as well as possibilities. With a mosaic behind a single optical system, we have the opportunity to use the large number of sources in the wide field to constrain the single optical distortion pattern. The challenge in this analysis is to converge on a solution for the detector positions, rotations, and possible tips, tilts, or higher order shape terms, such as warps, while also solving for the optical distortion. It is difficult to solve such a minimization problem directly because of the degeneracy between the per-chip terms and the optical distortion. We have approached this problem by measuring instead the local gradient of the optical distortion term, which is substantially less sensitive to the chip positions.

At the current time (Nov 2007), the PS1 telescope is in the process of being commissioned. The Gigapixel Camera obtained the first-light images on Aug 23, 2007. The most crucial and challenging aspect of the PS1 commissioning is the determination of the proper collimation and alignment of the telescope optics and camera. The wide-field optical design is very sensitive to the collimation, and precise mechanical alignment of the components *a priori* is not possible. The PS1 telescope has 5 axis control over the secondary mirror and 4 axis control over the primary mirror (displacement along the altitude axis is not active). The collimation process employs the observation of star fields with the M1 and M2 positions dithered about a local optimum. These observations are then compared with ray tracing models of the optical system in an attempt to predict the observed stellar shape variations, and thus predict the required motions of the other, uncontrolled elements, such as the corrector lens placement. Once confidence is obtained for a particular predicted move of one of the elements, the mechanical work needed shift or tilt or change the lens spacing may be performed. This work may require removing the camera or machining small components, and so requires 1 or 2 weeks of effort. It is expected to require several months to complete this somewhat laborious iterative process.

At the time of this writing, the image quality from PS1 was still substantially affected by aberrations as well as mirror seeing due to the unfinished cooling system. For example, a typical 'good' set of observations of the Pelican Nebula have stellar images near the field center with roughly Gaussian profiles and FWHM of 1.5–2.0 arcseconds, but which degrade to distended, irregular, multi-peaked shapes in the outer portions of the camera. After collimation and alignment is complete, the optical performance is expected to be dominated by the atmosphere, with an expected median seeing of ~ 0.8 arcseconds. Nonetheless, with the existing data, we can already demonstrate relative astrometry residuals between pairs of images which approach our error goals. In sample tests, we have obtained relative astrometry residuals between pairs of PS1 images across 50 of the 60 chips ranging from 35–50 milliarcsec. The remaining devices were either excessively aberrated for a solution or were contaminated by excessive dark current (also being tuned in commissioning). Given the poor image quality (and the factor of $\sqrt{2}$ increase in the noise due to the comparison of two images), these numbers are very much in line with our goal of 10 mas per observation.

We have performed simulations of our ability to measure parallax and proper motion for sources observed in the PS1 3π Survey, given the 10 mas error floor and the planned survey observing cadence. With the full set of 60 observations available at the end of the 3.5 year survey, we expect to measure proper motion with an accuracy of 1.2 mas/year, and parallaxes of 1.5–2.2 mas, depending on the ecliptic latitude. We have also examined the behavior of the proper-motion and parallax errors as we modify the available observations. For example, for those objects which are only detected in the y-band observations (e.g., ultracool brown dwarfs), the parallax accuracy is reduced because of the smaller number of detections to 2.9 mas.

4. The extended Solar neighborhood from PS1 astrometry

The PS1 3π Survey will be a transformational data set for a wide range of science areas. This paper addresses only the benefits for the study of the extended solar neighborhood, the region within a few hundred parsecs of the Sun, and in particular the low-mass and substellar populations. Some of the other topics, beyond the scope of this article, that will benefit from the improved astrometry resource include the studies of the Galactic dynamical structure, the large-scale streams and the Galaxy formation and evolution, and the impact on improved orbits for objects within our own Solar System. Other important topics within the context of the extended solar neighborhood include the discovery of nearby white dwarfs and the membership of moving groups. In this article, we will focus on two particular science topics: the parallax-selected field dwarf sample and the study of star forming regions via proper-motion selections.

4.1. *Field dwarf parallax sample*

The first generation of digital wide-field surveys (SDSS, 2MASS, DENIS) have contributed most of the discoveries of brown dwarfs and very low-mass stars to date (Delfosse *et al.*, 1999; Kirkpatrick *et al.*, 2000; Hawley *et al.*, 2002; Burgasser *et al.*, 2004). Although these ground-breaking surveys were highly sensitive and covered very large areas on the sky, the low luminosity and very red colors of the coolest dwarfs limit the total number of detected objects. The degeneracy of their optical and/or IR colors with reddened background giants and/or ordinary higher mass stars is also a major hindrance, introducing substantial contamination. In order to find an interesting number of confirmed very low-mass objects, color-selected samples must be further filtered, with proper motions, photometric distance indicators, or spectroscopy. As a result, the efficiency of these searches is limited, and require large amounts of follow-up time. Follow-up parallax measurements for these objects have been particularly time consuming.

The astrometric capabilities of the PS1 3π Survey will allow us to minimize the biases in the observational selection process, and to construct a very large sample of very low-mass stars and brown dwarfs. With such a sample, we will be able to address several key areas in our understanding of these ultracool objects. The multiple epochs and high astrometric precision will make the PS1 3π Survey the most sensitive single large-scale survey for parallax and proper-motions. The PS1 3π Survey will cover a much larger area than the SDSS, and will have a higher sensitivity to very low-mass stars and brown dwarfs as a result of its deeper magnitude limits and very red y-band filter. At 1μm, the PS1 system is roughly a factor of 10 more sensitive than SDSS. PS1 will be orders of magnitude more sensitive than the USNO-B survey for these red objects, and will be significantly more sensitive than the 2MASS survey for all but the reddest T dwarfs. Finally, the PS1 3π Survey will have very stringent photometric calibration requirements, yielding extremely high-quality magnitudes and colors.

By combining parallax and proper-motion measurements with precise photometric selections, the PS1 3π Survey will yield a wide-area sample of very-low-mass stars and brown dwarfs with an unprecedented level of characterization and reliability. Not only will this sample increase the number of known L and T stars by an order of magnitude, yielding thousands of L dwarfs and hundreds of T dwarfs with measured parallaxes (compared with the current total number of less than a 100), but their identifications will be extremely reliable and their basic properties will be well-determined largely without additional follow-up. The PS1 3π Survey will thus yield a gold-mine of an unbiased, volume-limited sample of very low-mass stars and brown dwarfs for a huge range of studies into the properties and evolution of ultracool objects.

4.2. *Star formation regions*

The nearby star forming regions represent an important keystone in the study of the star formation process. By studying the nearby star forming regions we observe a collection of objects formed within a common context, as with any cluster study. More importantly, the nearest clusters are sufficiently close that we can examine the faintest, lowest-mass objects in relation to the higher mass populations and apply detailed spectroscopic follow-up observations to these low-mass sources. Our current understanding of these regions is hampered by a variety of observational selection effects and biases. In particular, the completeness of the low-mass stars and substellar objects is often poor, spatially limited, and difficult to assess because of the heterogeneous selection processes.

The improvement from PS1 will come from two important features: first, the combination of the depth and large-area of the PS1 3π Survey will allow us to search for low-mass members associated with the star forming regions over a very large area. The full extent of nearby star forming regions such as Taurus, Ophichus, Upper and Lower Sco, cover many hundreds of square degrees on the sky. Surveys to date have either been shallow, using photographic plates or small telescopes with wide field, undersampled CCDs, to observe the entire regions; or else they have focused on the cores of these clouds with deep observations on large telescopes. The PS1 3π Survey will span these two regimes, pushing deep across the widest possible regions (north of -30 deg in Dec).

In addition to the wide, deep photometric coverage, the PS1 3π Survey will also use its proper-motion sensitivity to make a quantum leap in the study of the young star formation regions. With high-quality proper-motion measurements, we will be able to select the members of the these star forming regions with substantially higher reliability than prior single-epoch surveys. The photometric selection process is severely hampered by the degeneracy of spectral classes and extinction in the color-color planes, and the degeneracy between the combination of extinction and luminosity classes and distances. Using proper motions to pre-filter potential candidates before performing a photometric selection will allow us to greatly improve the completeness of the cluster membership lists. Even at the start of the survey, we will be able to use the 2MASS observations from the late 1990s as a first epoch for the initial proper motion measurements. These studies will be similar to recent results on the Pleiades based on proper-motion studies (e.g., Lodieu *et al.*, 2007), but will extend the spatial coverage substantially and increase the proper-motion accuracy.

We have been using the CFHT MegaPrime camera to perform a demonstration of this process, using archival CFHT data as a first epoch for the proper motion measurements. To date, we have observed 25 square degrees in Taurus and 10 square degrees in Rho Ophiuchus. Observations of several other nearby clusters are scheduled. The initial analysis of these data show the power of the technique. By applying our precision astrometry analysis to the MegaPrime observations separated by a baseline of 2.5 years, we are able to achieve proper motion measurements with an accuracy of 2.5 milliarcsecond/year. Selecting sources within 2σ of the Taurus proper motion vector reduces the number of potential candidates which would be selected photometrically from $\sim$2200 to 73 (for an initial 10 square degree subset). We are currently scheduled to observe these targets with the IRTF in Nov 2007 to identify the young dwarfs and confirm their membership.

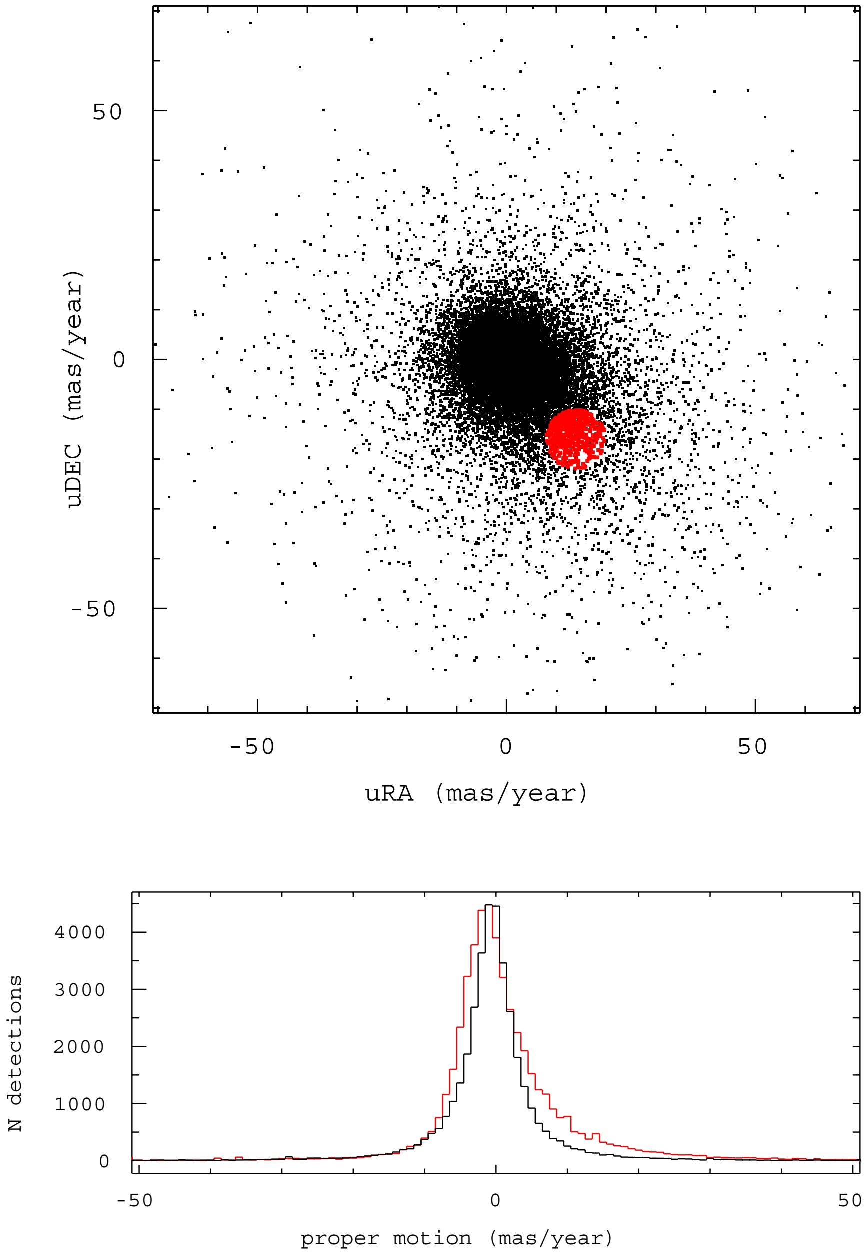

Figure 1. Our proper motion measurements for faint objects in the field of Taurus, based on CFHT i-band. Sources within 6 mas/year of the Taurus velocity are indicated in red. The histogram above shows the cuts along (red) and perpendicular (black) to this velocity vector.

5. Conclusions

The PS1 Project will soon begin the PS1 3π Survey, covering the 3/4 of the sky visible from Hawaii with many repeated observations over 3.5 years. The high-quality astrometric and photometric measurements expected from this survey will be a treasure

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trove for research covering a wide range of Galactic astronomy. The parallax accuracy ($\sim$1.5 mas) will enable the creation of volume-limited samples of low-mass stars and brown dwarfs in the extended solar neighborhood out to roughly 100pc. The proper-motion accuracy of 1.2 mas/year will allow for the identification of the currently missing members of the nearby star formation regions. The PS1 telescope is in the process of being commissioned, and preliminary astrometric tests show the accuracy goals should be achievable. Survey operations are expected to begin in mid-2008.

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