

Ground-Based Astrometry 2010-2020

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Abstract

We discuss the opportunities for astronomical discovery via ground-based astrometry carried out in the United States during the 2010-2020 decade. We describe imminent scientific breakthroughs that can be achieved at both classic astrometric scales — narrow angle astrometry done by individual groups and large $A^*\Omega$ astrometry carried out by consortia. The two most compelling questions to be addressed are (1) *What is the composition of the stellar and substellar population near the Sun?* and (2) *What are the shape, size, and mass of the Milky Way?* We provide a short list of five recommendations that we believe will allow us to take best advantage of the intellectual and financial investments made for what some have called “The Decade of Astrometry.” The most important recommendation is to provide the educational foundation required so that a new generation of astrometrists can make best use of the rich datasets that will arrive in the coming decade.

1 Introduction

Without a map, astronomers are lost.

The astronomical endeavor to understand the positions of objects in the sky, or astrometry, is the foundation of our comprehension of the Universe. Astrometry provides both the (X,Y) positions on the sky necessary for coordinates, as well as the all-important third dimension, distance, that astronomers spend so much of their time trying to measure. One of the basic, yet most important, measurements in astronomy is the trigonometric parallax, which forms the fundamental rung in the astronomical distance ladder.

Advances in astrometry have always been driven by technology, advancing from the human eye to modern telescopes and space satellites. On the ground, CCD mosaic cameras on medium-sized telescopes are now offering enormous amounts of data with milliarcsecond (mas) relative positions, and radio interferometers have already leapt into the microarcsecond (μ as) regime with recent results from the VERA radio interferometric array (Honma et al. 2007) and the VLBA (Reid et al. 2008). In space, we are poised to reach such precision on a grand scale in optical astrometry with missions such as *J-MAPS*, *Gaia*, and *SIM*. Such precision makes it possible to do research at the forefront of astronomy using astrometric techniques in a way never before possible.

Our goal here is to anticipate the forthcoming breakthroughs in astronomy given sufficient support for astrometric programs in the coming decade. We focus specifically on major questions that can be solved by measuring parallaxes and proper motions, while leaving detailed discussions of binary stars and exoplanet searches to other white paper efforts. Throughout, a central theme should be remembered — the next decade will deliver more astrometric data with greater accuracy to more users than the sum of all previous astrometric endeavors. Surprises are guaranteed.

2 A Note about Space-Based Missions

The Decadal Survey Committee will hear separately from those involved in space-based astrometric efforts, so we only briefly mention them here for context. *Hipparcos* (Perryman 2008) revolutionized astrometry a decade ago by providing positions and parallaxes for fairly

bright stars to ~ 1.0 mas, and with refinement, the accuracy for some stars is now ~ 0.5 mas (van Leeuwen 2007). *HST*'s Fine Guidance Sensors make it possible to obtain relative parallaxes to 0.2 mas accuracy for dozens of fainter stars of special astrophysical interest (e.g., Benedict et al. 2008), and to help calibrate the Galactic Cepheid distance scale.

In astronomy, one can always play the waiting game until something better comes along. There are at least four significant space-based efforts that may be launched in the next ten years, each of which has its niche: ESA's *Gaia*, scheduled to launch in 2011 with final results due in 2020, will increase distances accurate to 1% from the 10^5 stars measured by *Hipparcos* to 10^7 stars with magnitudes 6–15, with upper limits on parallaxes for perhaps 10^9 stars. USNO's *J-MAPS*, slated for a 2012 launch, will measure 10^7 stellar parallaxes to 1 mas with magnitudes 0–14 (results due in 2016), and creates a 20-year proper motion baseline for bright stars when linked to *Hipparcos* (bright stars will saturate in *Gaia*). Japan's planned infrared *JASMINE* spacecraft (launch date not set) targets 10^8 stars in the Galactic bulge to $z \sim 14$. The future of NASA's *SIM* remains uncertain, but it could observe 10^4 stars with precisions at the μ mas level and would reach to magnitude 20. Even if all four are successful, it must be stressed that not all high-accuracy astrometry will be done with space satellites — narrow angle astrometry in the next few years will provide scientific breakthroughs that will merge into the large $A^*\Omega$ surveys that will soon follow.

3 Narrow Angle Science: The Solar Neighborhood

The long history of ground-based astrometric work dates back to the efforts of Hipparchus, Brahe, Galileo, and Kepler (among others), with a specific breakthrough in 1838 by Friedrich Bessel, who measured the first stellar parallax, for the nearby binary 61 Cygni. The latest ground-based parallax compendium is the General Catalog of Trigonometric Parallaxes (van Altena et al. 1995), which includes parallaxes for 8112 stars measured to a few mas. Since then, roughly 700 total parallaxes have been published, typically accurate to ~ 1 mas (see www.RECONS.org). The total number of targets among current parallax programs is ~ 1000 . The target lists come from classic work such as Luyten's (1979), to more recent all-sky surveys such as 2MASS, DENIS, and SDSS. Follow-up narrow angle investigations pinpoint the most intriguing sources, often at the faint limits of such surveys, from which the science is squeezed out when precise astrometric techniques are applied. We list here some of the most important questions that can be answered during the next decade by targeted optical, infrared, and radio astrometry of individual sources. This work forms both the scientific and educational foundations for our fundamental, and important, transition to the large $A^*\Omega$ projects that will expand each sample markedly during the next decade.

- *What is the stellar population near the Sun?* The number of stellar systems known within 10 pc has increased by 18% since 2000 (Henry et al. 2006; www.RECONS.org), thereby tipping the stellar mass function significantly to the smallest stars. A more accurate local census can be used to challenge star formation theory, provide a benchmark for missing mass evaluations, and provide key targets for major planet hunting missions. A complete understanding of the multiple star population will be forthcoming via detailed astrometric studies at all separation scales larger than ~ 10 mas.

- *What are the natures and number fractions of various types of brown dwarfs?* Great advances have been made in understanding a few dozen substellar objects because parallaxes are now available (Dahn et al. 2002; Vrba et al. 2004), but our knowledge of their true

space density is rudimentary at best. High accuracy astrometry at infrared wavelengths in particular is a nascent field, and breakthroughs in brown dwarf research are imminent as large sky surveys come online and push to fainter magnitudes. By 2020, we will know the relative populations of stars and brown dwarfs.

- *How many white dwarfs are there in the Galaxy?* White dwarfs are important chronometers for age-dating Galactic components, but their number densities in the disk and halo are poorly known. Even within 25 pc the number of known white dwarfs has climbed 25% since 2000 (e.g., Subasavage et al. 2009). In addition to affecting our understanding of the initial mass function, these are the objects that will be used for severe tests of degenerate matter theory, as they provide the highest fidelity spectra and will provide the most accurate masses.

- *How much mixing of ancient subdwarfs is there in the Sun's vicinity?* Subdwarfs are outnumbered 100:1 by their main sequence counterparts and are consequently poorly understood. The first comprehensive sample of subdwarfs within 60 pc is being constructed now (Jao et al. 2009). Continued identification of subdwarfs via large-scale astrometric surveys with followup (or concurrent) parallax efforts will lead to an enhanced understanding of the complex age and metallicity mixing of the Galaxy's components.

- *What types of unseen companions are found orbiting stars?* One of the significant advantages of ground-based work is the duration of the astrometric series. The large surveys planned on the ground and in space typically have five-year horizons, whereas some ground-based surveys span a decade already (RECONS, USNO). Such surveys are exploring new territory for the types of unseen companions sampled, including brown dwarfs and exoplanets with orbital periods longer than Jupiter's. In the foreseeable future, only ground-based astrometry programs can provide multi-decade coverage.

- *What can stellar clusters tell us about stellar evolution and populations?* Star clusters provide us with laboratories to study the formation and evolution of stars, with the only major variable left being the stellar mass. Current proper motion measurements now allow us to identify cluster members to magnitude 21, thereby permitting us to reach nearly the end of the stellar main sequence out to 100 pc in various cluster environments (Platais et al. 2003; Vieira et al. 2005). High-precision astrometry will also allow us to pin down the mass-luminosity relations in fundamental clusters.

4 Narrow Angle Science: The Milky Way and Beyond

Beyond the immediate solar neighborhood lurk the rare members of the Milky Way and fundamental stellar clusters such as Orion, for which we now have a distance known to better than 2% (Menten et al. 2007). We are only just beginning to measure accurate distances to such sources, and even today we only have an educated guess about the number of spiral arms in our own Milky Way, or whether it is a barred Sb or Sc galaxy. Recent advances have been made at optical wavelengths with improved detectors and observing techniques to achieve sub-mas parallax errors, while at radio wavelengths, high-intensity masers can be targeted interferometrically to provide parallaxes with errors as small as 10 μ as. These capabilities open up new territory for exploration through the Milky Way and into the hearts of nearby galaxies. A few parts of the territory that will expand in the next decade are highlighted here.

- *What are the characteristics of rare members of the Galaxy, such as cataclysmic variables and the central stars of planetary nebulae?* Concerted efforts on CVs at optical wave-

lengths have yielded reliable distances for many, giving empirical heft to estimates of luminosities, white dwarf masses, and (ultimately) space densities (Thorstensen et al. 2008). Because of ground-based parallax efforts on planetary nebulae central stars, we now know their luminosities and how they bridge the gap between massive stars and white dwarfs (Harris et al. 2007). Anticipated improvements in parallax measurements will expand these samples by a factor of ten (or more) in the coming decade.

- *What is the distribution of luminous and dark matter in the Galactic disk?* Different surveys give conflicting results, although there may be some convergence towards the amount of luminous matter being substantial and the amount of dark matter being small (Girard et al. 2006). To investigate, a survey with the WIYN One Degree Imager covering 100 square degrees would provide parallaxes with an accuracy of ~ 0.5 mas to magnitude 21. The derived robust stellar and brown dwarf samples out to 150 pc will provide reality checks for the large $A^*\Omega$ surveys discussed below.

- *What are the shape, size, and mass of the Milky Way?* Recent improvements in radio astrometry with the VLBA have yielded parallaxes and proper motions to star forming regions across a significant portion of the Milky Way with accuracies of $\sim 10 \mu\text{as}$ and a ~ 1 km/s, respectively (Reid et al. 2008). In the next decade or so, we could measure the position to every high mass star forming region in the Galaxy and provide a three-dimensional map, complete with three-dimensional velocity vectors. This would yield the distance to the Galactic center (R_0), the rotation speed of the LSR (Θ_0), the form of the rotation curve, and the kinematic effects of spiral structure. In conjunction with the astrometrically-determined proper motions of Milky Way satellite galaxies and improved numerical simulations, we will learn the size and mass of the disk, bulge, and dark matter halo of the Milky Way.

- *How many dwarf galaxies are orbiting the Milky Way and what are their orbits?* Lambda cold-dark matter (LCDM) cosmological models predict debris left from several hundred merging dwarf galaxies within one kiloparsec of the Sun (Helmi & White 1999). To date, only a handful of possible candidates have been identified, which casts doubt on the validity of the model. Alternatively, we may not yet have found these faint objects. The proper motions from deep, wide surveys would reveal dozens of streams within a few kpc, if they exist, thereby stress-testing the LCDM model. Orbits such as those measured by Dinescu et al. (2005) for the Sgr dwarf are key to testing the LCDM model on small scales where it is most challenged. Such orbits allow us to understand whether these satellites are of tidal and/or cosmological origin (better defining the missing satellite problem) and to estimate their masses by properly quantifying the input from tides.

- *What is the proper motion of the Andromeda Galaxy?* Andromeda’s three-dimensional motion is key to understanding the history and fate of the Local Group. Andromeda’s proper motion can be measured via radio astrometry in the coming decade, and when combined with available velocity information, its derived three-dimensional motion will allow us to understand the delicate (or not) dance of Andromeda and the Milky Way.

5 Large $A^*\Omega$ Surveys: Rich Data Mines

The grand ground-based sky surveys completed using the Palomar, UK, and ESO Schmidt telescopes, and the subsequent digitizing of thousands of photographic plates (USNO’s PMM, U. Edinburgh’s SuperCOSMOS, and STScI’s DSS), revolutionized the way astronomers work by providing huge datasets of astrometric and photometric data. More recently, SDSS,

2MASS, and DENIS have provided significant datasets using modern CCD and infrared array detectors. The next generation of ground-based sky surveys is imminent, and these efforts will produce substantial science before, in parallel, and beyond (in both time and phase space) what space missions promise. All of the previously mentioned science avenues that profit from ~ 1 mas parallaxes and proper motions (and high quality photometric data) will benefit from these efforts, with target lists that expand up to 10^{10} objects. Here we describe four of the most comprehensive astrometric surveys, and then concentrate on one application — studies of the very nearby stars.

The key technologies that make the large etendue ($A^*\Omega$) systems possible are (a) large mosaics of CCDs, (b) the reduction in physical size and power dissipation for the CCD electronics, (c) telescope optics with exquisite image quality over a large fields of view, (d) computer hardware and software that enable the scientific processing of many terabytes of data/night, (e) databases that can store and query these large data volumes, and (f) high-bandwidth communication networks to distribute the results. We are now experiencing nothing less than a “perfect storm” of the necessary technologies. Each of the surveys discussed here can provide parallaxes (or upper limits) for every star in the sky surveyed to their limiting magnitudes because multiple visits are made to each region. All surveys understand the importance of astrometry and all are inserting astrometric processing into their data processing pipelines.

- *Pan-STARRS (Panoramic Survey Telescope And Rapid Response System)*: Led by the Institute of Astronomy of the University of Hawaii, the first Pan-STARRS telescope (of four planned) achieved first light in 2006. Pan-STARRS plans to survey 30000 square degrees on $0.3''$ pixels to magnitude 24 (single visit).

- *SkyMapper*: Based at Siding Spring Observatory, SkyMapper achieved first light in 2008. During the planned Southern Sky Survey, 20000 square degrees will be imaged in six optical filters on $0.5''$ pixels to magnitude 21 (single visit). A shorter-integration survey is planned to sample stars with magnitudes 9–16.

- *URAT (USNO Robotic Astrometry Telescope)*: Following the successful USNO CCD Astrograph Catalog (UCAC), URAT (Zacharias 2008) will employ telescopes in both hemispheres to cover the entire sky in two phases — phase one for $R = 7\text{--}18$ and phase two to $R = 21$. Pixels on the sky are $0.5\text{--}0.9''$ in size. Unique to URAT is its importance in providing absolute proper motions on the ICRF over the *entire sky*, thereby providing a fundamental reference frame for both ground- and space-based programs. A key component is that the survey bridges the *Hipparcos* and *Gaia* missions, which allows proper motions to be distinguished from orbital motions measured over short periods.

- *LSST (Large Synoptic Survey Telescope)*: Led by the LSST Corporation, the magnitude 25 limit (single visit) of LSST is extraordinary, as are the $0.2''$ pixels used to sample the sky in six optical filters. First light is planned for 2015 and several hundred observations of each piece of sky are likely. Thus, parallaxes and proper motions can be determined for huge samples that will not be observed by any other ground- or space-based effort.

Among the “lowest hanging fruit” to be picked from these surveys is the study of stellar populations. All stellar types within 10 pc and most stellar types to 100 pc will have accurate parallaxes measured in only a few years. The end of the stellar main sequence falls near $M_V = 20$, so all of the above surveys will find all stars within 10 pc. At 100 pc, the end of the main sequence is $V = 25$, which will be sampled only by LSST, but all four surveys will reach at least M4.0V type, as well as all but the coolest white dwarfs and subdwarfs. The luminosity

function for such stars can be measured once and for all, and because high quality, multi-color photometric data will also be collected, credible physical models can be constructed. Bright brown dwarfs will also be comprehensively sampled by LSST and Pan-STARRS. Even for the reconnaissance of the solar neighborhood, a synergy of astrometric efforts on the ground and in space is required because various efforts sample different magnitude ranges — some saturate where others are most sensitive, while some reach deeper than others can reach. The decade 2010-2020 will, for the first time, provide that synergy.

6 Education in Astrometry

The potential for astrometry to contribute to science is greater than at any time in history. A desperate need exists to train young scientists in astrometry to make the most of this exciting future. We have outlined above myriad scientific questions that can be answered during the next decade by continuing ground-based astrometry, yet all of these are moot if no one knows the techniques needed to produce the science.

If we are to take advantage of the science opportunities made possible by the advent of μs astrometry, we need to reformulate our study of reference frames, systems, and the equations of motion in the context of special and general relativity. Methods need to be developed to statistically analyze our data and calibrate our instruments to levels beyond current standards. As a consequence, our curricula must be drastically revised to meet the needs of students in the 21st century (van Altena & Stavinschi 2008). Significant investments must be made by universities in the US to hire specialists to teach new generations of scientists how to guide the development, optimize the use of, and analyze the data from advanced instrumentation with astrometric capabilities. This is a critical problem. Not one university in the US has hired a specialist to teach astrometry for many years and there is currently no formal astrometry course being taught in the US. Aside from the US Naval Observatory, not one of the major observatories, e.g., KPNO, CTIO, Gemini, Keck, Pan-STARRS, LSST, etc. has a specialist in the field on its staff (except for D. Monet, who is doing at least double duty). Even more stunning is that the NSF has not funded a single proposal in optical astrometry for the last two years. This situation must be rectified in the coming decade or our national investments in both ground- and space-based astrometric missions will be severely compromised.

7 Astrometry Short List 2010-2020

1. We recommend that NSF and NASA consider funding ~ 10 tenure-track scientists to carry out significant astrometric programs in university environments where students can learn the tools of the trade. Currently in the United States there are fewer than five tenured faculty whose primary science is centered around classical astrometry. Ideally, this number would be at least doubled during the next decade to (a) allow the science to advance, (b) provide students opportunities to learn, and (c) support the complex astrometric needs for major projects planned that will commence in the next decade and carry into 2020-2030.

2. We recommend that telescopes with apertures less than 4m be supported through the next decade so students obtain real experience making astrometric observations. To take advantage of the upcoming expensive ground- and space-based

astrometric efforts, meaningful, hands-on experience for young astronomers is needed, and is most easily carried out on relatively small telescopes. Of course, appropriately stable imaging instrumentation, ideally with AO for diffraction limited observations, is also needed.

3. We recommend that in the area of radio astrometry, upgrades in receivers and data recording equipment be made at the VLBA. Specifically, adding a new receiver capable of observing the ubiquitous 6.7 GHz methanol masers is needed to map the locations and motions of hundreds (instead of tens) of star forming regions across the Milky Way. Upgrading the VLBA data recording rate by two orders of magnitude would dramatically improve astrometric accuracy by making far more background quasars available as positional references. The construction of a high frequency “SKA” capability would revolutionize radio astrometry and lead to truly dramatic results beyond the Local Group.

4. We recommend that a few programs be identified for multi-decade, consistent, astrometric research so that unique long time domains can be sampled. Perhaps the single most important reason to support narrow angle, ground-based astrometry during the next decade is because long-term astrometric series open new parameter space unmatched by any of the large efforts, which typically have horizons of five years. Many small telescopes allow for this capability, and some large telescopes, e.g., Keck, are making moves toward long-term possibilities.

5. We recommend that data mining opportunities for students and database management tools be supported so that the next generation of astronomers can take advantage of the wealth of data that will pour out of the astrometric surveys. In the age of terabytes of data/night, we will certainly be limited by our efficiency in sifting through the data mountains for the few gems that matter. Only with astute planning can the exquisite science happen, or we have forfeited our opportunities and our resources.

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