

The UCAC3 Star Catalog: A New Catalog of Optical Reference Stars for Space Surveillance

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Abstract

Version three of the U.S. Naval Observatory CCD Astrograph Catalog (UCAC3) was released in August 2009. As the first version of the UCAC to cover the entire sky, UCAC3 is a suitable source of optical reference stars in the $R = 8$ to 16 magnitude range. Containing just over 100 million objects and providing stellar positional accuracies of about 15 to 100 milliarcseconds (mas) per coordinate, UCAC3 provides a background reference stellar grid considerably denser than either the Hipparcos or Tycho Catalogues. Approximately 95 million objects in the catalog have listed proper motions, derived by combining UCAC observations with over 140 ground- and space-based catalogs, both published and unpublished. Proper motions are provided with an accuracy of 1 to 10 mas/yr, depending on magnitude and observing history. Major differences between UCAC3 and the two preceding versions of UCAC include all-sky coverage, a completely new raw data reduction with improved control over systematic errors in positions, significantly improved photometry, slightly deeper limiting magnitude, and much greater completeness by inclusion of double stars and weak detections.

In addition to a review of UCAC3, we discuss the status of other star catalogs suitable for space surveillance and provide an update on several programs expected to produce bright- and faint-star catalogs of potential future interest to the space surveillance community.

Introduction

The history of astrometric measurements over two millennia is indicated in Figure 1. There have been significant improvements in the reference system and star catalogs in the last 15 years. The Fifth Fundamental Catalog (FK5) (Fricke et al., 1988) reference system and catalog has been replaced by the International Celestial Reference System (ICRS) and the Hipparcos Reference Catalogue (1997). This has improved accuracies from tenths of arcseconds to milliarcseconds (mas).

The ICRS is a fixed reference system that is independent of epoch. The International Celestial Reference Frame (ICRF) is the reference frame implementing the ICRS. The second edition of the ICRF (called ICRF2) was adopted in 2009 (Boboltz et al., 2010). However, we observe from the Earth, which has kinematic motions affecting the positional observations. A new non-rotating origin, the Celestial Intermediate Origin (CIO), has been introduced to replace the equinox. A new precession-nutation model has been developed with considerably

improved accuracies. The Celestial Intermediate Pole (CIP) has replaced the Celestial Ephemeris Pole (CEP) as the reference pole.

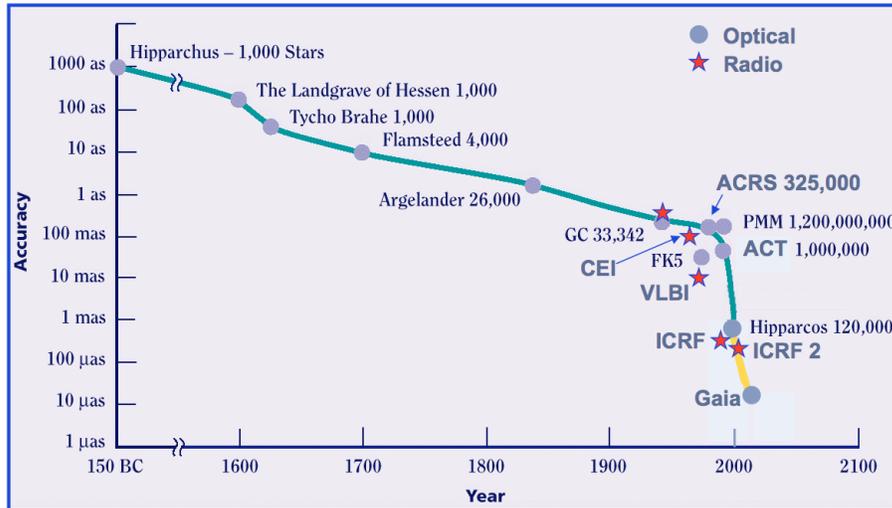


Figure 1. Past Progress in Astrometric Measurements

Star catalogs on the ICRS have been developed to densify and to reach fainter magnitudes for reference stars. However, with time the uncertainties of proper motions degrade the accuracies of the reference stars' positions. Thus, there is a need for continuing accurate observational programs to maintain and to improve the reference star accuracies. A series of ground-based, dedicated astrometric, observational programs have been performed or are in preparation, which provide a dense and accurate optical reference frame. Integral to all these programs are new observations to link the Hipparcos Celestial Reference Frame (HCRF) to the ICRF, based on compact, extragalactic radio sources.

The third U.S. Naval Observatory CCD Astrograph Catalog (UCAC3) was released in 2009. Optical counterparts of ICRF radio sources have been observed with 0.9-meter telescopes contemporaneously. Scanning of over 5,000 early-epoch astrograph plates on StarScan has been completed (Figure 2). These data improve the proper motions of stars in the 10 to 14 magnitude range.

A 111 million-pixel CCD was successfully fabricated in 2006 and test observations at the USNO astrograph were performed. Four such detectors will be used for the USNO Robotic Astrometric Telescope (URAT) focal plane assembly. URAT will use the astrograph to reach 18th magnitude.

Reference System

The ICRS is a space-fixed, barycentric astronomical reference system based on the availability of Very Long Baseline Interferometry (VLBI) observations of distant, extragalactic, (thus non-moving) radio sources. Thus, the FK5 reference frame, based on bright nearby (thus moving) stars, and a dynamical frame determined from solar system motions, has been replaced. The new frame was defined to be close to the previous reference frame specified by the FK5 at J2000.0, within the errors of that frame. The x-axis of the ICRS points as closely as possible to the dynamical mean equinox of

J2000.0. The ICRS is defined by a series of International Astronomical Union (IAU) resolutions in 1992, 1998, 2001, and 2006.



Figure 2. Star Scan plate measuring machine in Washington DC

Improvements in the observational accuracies and the corresponding improvements in theories have driven most of the above changes. VLBI has achieved sub-milliarcsecond accuracies for observations of extragalactic radio sources. The Hipparcos Catalogue contains positions, proper motions, and parallaxes with milliarcseconds accuracy. At these accuracy levels, the definitions of the reference systems and the methods of reduction and analysis require the theory of relativity.

In order to define rigorously the ICRS in relativistic terms, the IAU introduced two systems: one at the barycenter of the solar system (the Barycentric Celestial Reference System, BCRS), and one at the geocenter of the Earth (the Geocentric Celestial Reference System, GCRS). Both have post-Newtonian metric tensors with a generalized Lorentz transformation between them that contains the acceleration of the geocenter and the gravitational potential. The BCRS is assumed to be oriented according to the ICRS axes. The BCRS and GCRS have no kinematic rotation between them, but they have different time coordinates, specifically Barycentric Coordinate Time (TCB) and Geocentric Coordinate Time (TCG), respectively.

The ICRF is defined by about 200 primary radio sources, which give the frame an accuracy of about 30 microarcseconds (μas). The ICRF is the realization of the ICRS by radio sources. The coordinate axes of the ICRF are fixed and not a function of time, to the accuracy of the system of VLBI observations. The ICRS does not depend on either the pole of rotation of the Earth or the pole of the ecliptic, which are now subjects of observation. The ICRF2, adopted by the IAU in 2009 and implemented January 1 2010, is an even more accurate reference frame containing many more sources, based on a decade of additional VLBI observations. The system of the ICRF2 is the same as the system of the original ICRF within their errors.

The realization of the ICRF in optical wavelengths comes from those stars in the Hipparcos Catalogue without problem flags. This catalog has an uncertainty with respect to the ICRF of 0.25 mas/yr in rotation and 0.60 mas in the position of the origin at epoch 1991.25 (Kovalevsky et al.,

1997). The ICRF is valid for all dates. To determine astrometric positions on the ICRF for specific dates, the star positions only have to be corrected for their proper motions (and parallax, if known).

While the ICRF is a space-fixed frame, the Earth still has many variable motions. There is still the need for a moving reference frame of date that is based on the true Earth equator of date. However, the moving reference frame does not have to be tied to a dynamical reference frame. The IAU established a new moving reference frame of date defined by a kinematic system based on the motions of the observing platform, the Earth, rather than a dynamical system based on solar system motions. As an alternative, the moving reference frame tied to a dynamical reference frame defined by the solar system is still in use. Both systems are expected to be used and data will be provided in each for an extended period of time.

Although the definition of this new moving reference frame is arbitrary, continuation of past methods is clearly desirable where possible. To accomplish this, the IAU introduced new concepts and definitions including a new combined precession-nutation model (including precession corrections and geodesic precession and nutation), called IAU2000A. There are two versions of the model: IAU2000A is accurate to 0.1 mas, while IAU2000B is accurate to 1 mas. In the models there are no terms with periods shorter than 2 days. All periodic terms less than two days are included in polar motion. Geodesic precession and nutation, which are very different effects than the regular precession and nutation, are included in the new models. Free core nutation is not included in the models.

The new IAU 2006 Precession Theory, based on Capitaine et al. (2003), was adopted in 2006 (Hilton et al., 2006). This precession theory should be used with the nutation model of IAU 2000A for best accuracies. The new precession theory provides accurate means of determining mean and true positions in the “equinox-based” system. The IAU defined a new Celestial Intermediate Pole (CIP), determined by the precession-nutation model. The CIP is the pole of the intermediate equator of date. The IAU introduced the word “intermediate” for the reference frame between the celestial and terrestrial reference frames.

Since the ICRS is independent of the moving equinox, there is no need for the orientation of the x-axis, or departure point, of the moving reference frame of date to be tied to the equinox. After considering a number of possible choices for a departure point, the Celestial Intermediate Origin (CIO) was chosen as an alternative to the equinox. The CIO is defined such that its motion on the fixed sphere has no motion along the instantaneous equator. This means that the movement of the CIO is always at right-angles to the instantaneous equator. The CIO has been called the non-rotating origin in previous papers (Guinot, 1979). The angle, called the Earth Rotation Angle (ERA), measured along the equator between the CIO and the Terrestrial Intermediate Origin (TIO), in the International Terrestrial Reference Frame (ITRF), is such that it yields UT1 through a strictly linear relation. The time derivative of UT1 is proportional to the instantaneous angular velocity of the Earth. The location of the CIO on the equator is defined by an integral that involves the path of the precessing-nutating pole since the reference epoch (Capitaine et al., 1986). This can be computed from the precession-nutation model and from observations. The position of the CIO has a zig-zag secular motion across the ICRF over long periods of time (tens of thousands of years). The hour angle of the CIO is the ERA, which is equivalent to sidereal time, and is the replacement for the Greenwich Apparent Sidereal Time (GAST). The origin of the GAST is the equinox, which has components of motion along the equator. These are due to the motion of the equator and ecliptic with respect to each other. Thus, the relationship between GAST and UT1 includes terms due to precession and nutation. The ERA, and its relation to UT1, does not depend on the combinations of precession and nutation.

The International Terrestrial Reference System (ITRS) is defined by the International Union of Geodesy and Geophysics (IUGG, 1992) and is represented by the ITRF, which is a catalog of positions and velocities of point marks on the Earth. The longitude origin in the ITRF is the TIO.

Based on the ICRF definition of a fixed reference frame and its realizations, there are two different moving reference systems of date being used now: one is the improved theory of precession, the nutation model, current values of constants, and the equinox-based moving reference frame; and the second is the new system with the CIO for the origin of the moving system, the new precession-nutation model, and the current values of constants. These systems are referred to as “equinox-based” or “CIO-based”. Right ascensions may be measured from either the equinox or the CIO in the moving frames, and may also be given in the ICRF in the fixed frame. The terminologies “equinox right ascensions” and “CIO right ascensions”, respectively, can be used. CIO right ascensions and declinations are also called true, or intermediate, positions. The “equation of the origin” is the distance between the CIO and the equinox along the intermediate equator, the sign of the quantity being such that it represents the CIO right ascension of the equinox, or equivalently, the difference between the ERA and GAST. More information about the new reference systems and their implementation can be found in Kaplan (2005), Seidelmann and Kovalevsky (2002), Kovalevsky and Seidelmann (2004), IERS Conventions (2003), and IAU Transactions (1992, 1998, 2001, and 2006).

ICRS/ICRF

The intrinsic radio structure of the extragalactic sources is one of the limiting errors in the definition of the ICRF. There is ongoing work to monitor the structural evolution of the ICRF sources by using the Very Long Baseline Array (VLBA) and other VLBI telescopes around the world. Based on more than 5000 VLBI images produced from such observations, the astrometric suitability of 80% of the ICRF sources have been assessed. The number of VLBI images for a given source varies from one, for the least-observed sources, to more than 20 for the intensively-observed sources. From this analysis, a subset of 194 sources were identified that are highly compact at all available epochs. Such sources are prime candidates to define the ICRF with the highest accuracy (Charlot et al. 2008).

Over 500 counterparts of ICRF sources were observed during 24 deep CCD observing runs as part of the USNO CCD Astroglyph Catalog (UCAC) project, providing a direct link to Tycho-2 stars. For some sources a positional accuracy of 10 mas is achieved. A sample of 12 extragalactic ICRF sources are being observed at the Naval Observatory Flagstaff Station (NOFS) 1.55-meter telescope over several years to monitor optical position stability. First, high resolution images of selected sources were obtained at the Lick 3-meter AO system to correlate source structure with optical-radio centroid offsets. As part of the Space Interferometry Mission (SIM) preparatory science, about 240 bright QSO's are being monitored for photometric variability in B, V, R and I. The USNO Robotic Astrometric Telescope (URAT) will be able to combine deep CCD imaging of all ICRF2 target areas and millions of compact galaxies with a stellar, astrometric, all-sky survey at multiple epochs (Zacharias et al., 2008).

The Very Large Array (VLA), linked with the Pie Town Very Long Baseline Array antenna, has been used to determine astrometric positions of 46 radio stars in the ICRF. Positions were obtained in the ICRF directly through phase referencing of the stars to nearby ICRF quasars, whose positions are accurate at the 0.25 mas level. Radio star positions are estimated to be accurate at the 10 mas level, with position errors approaching a few milli-

arcseconds for some of the stars observed. The measured positions were combined with previous measurements, taken from as early as 1978, to obtain proper motion estimates for all 46 stars with average uncertainties of 1.7 mas/yr. Reference frames produced from radio star positions and the Hipparcos Catalogue data were compared, and consistency in the frames was found at the 1-sigma level, with errors of 2.7 mas per axis for the orientation angles at the mean epoch of 2003.78. No significant spin was found between the radio data frame and the Hipparcos Celestial Reference Frame (HCRF), with the largest rotation rates of +0.55 and -0.41 mas/yr around the x and z axes, respectively, with 1-sigma errors of 0.36 mas/yr. Thus, the results are consistent with a non-rotating Hipparcos frame with respect to the ICRF (Boboltz et al., 2006).

Astrometric and imaging results for compact extragalactic objects observed with the Very Long Baseline Array at radio frequencies of 24 and 43 GHz have been investigated. Data were obtained from ten 24-hour observing sessions made over an approximately 5-year period. These observations were motivated by the need to extend the ICRF to higher radio frequencies to enable improved deep space navigation after 2015 and to improve state-of-the-art astrometry. With observations over five years, a precision at 24 GHz approaching that of the ICRF was achieved, but systematic errors, such as residual tropospheric and ionospheric refraction, limit the overall accuracy of the catalogs. The reduction in the effects due to source structure gained by observing at higher frequencies will result in an improved celestial reference frame and a pool of high-quality fiducial reference points for use in spacecraft navigation over the next decade (Fey et al., 2009).

The XXVIIth General Assembly of the IAU recently voted to adopt the second realization of the International Celestial Reference Frame (ICRF2) as the fundamental astrometric reference frame, effective 01 January 2010. ICRF2 contains precise positions of 3,414 compact radio astronomical sources, more than five times the number in the first realization of the ICRF (ICRF1). Furthermore, ICRF2 is found to have a noise floor of approximately 40 microarcseconds, some 5-6 times better than ICRF1. The axis stability of the frame is roughly 10 microarcseconds, nearly twice as stable as ICRF1. Alignment of ICRF2 with the ICRS was achieved using 138 stable sources common to both ICRF2 and ICRF1. Future maintenance of ICRF2 will be accomplished using a set of 295 new "defining" sources selected on the basis of positional stability and the lack of extensive intrinsic source structure (Boboltz et al., 2010).

Current Catalogs

While the ICRF can be determined and maintained to an accuracy of about 0.2 mas, the extragalactic radio sources serving as its basis are optically faint. For this reason and the fact that the ICRF is too sparse for practical use, alternative implementations are required at optical wavelengths. Accuracies and densities of star catalogs are shown in Figure 3.

The Hipparcos Reference Catalogue resulted from the European Space Agency astrometric satellite mission from 1989-1993. About 120,000 stars down to 11th magnitude were observed as the primary mission of Hipparcos. About 100,000 catalog stars without problems are the basis for the implementation of the ICRS at optical wavelengths in accordance with an IAU resolution in 2003. At its mean epoch of 1991.25, this catalog is accurate to about 1 mas per coordinate, but since the proper motions have about 1 mas/year uncertainties, the accuracy of the catalog is continually degrading. Current positional

accuracies of approximately 20 mas (standard error) can be expected, with some individual stars having much larger errors.

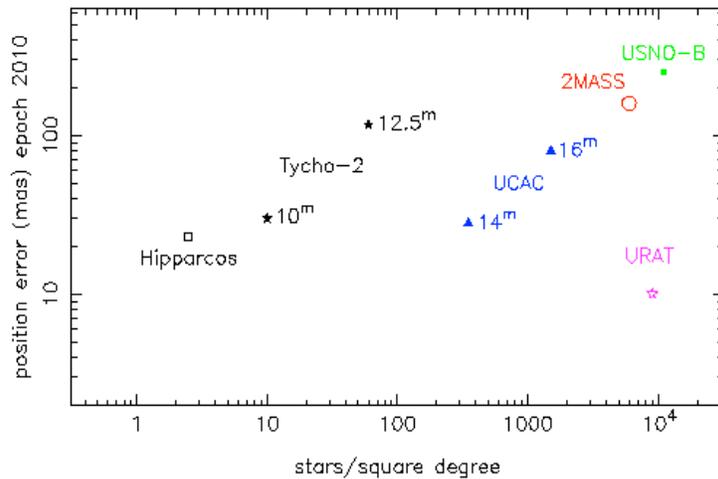


Figure 3. Accuracy and density of star catalogs

The Tycho 2 Catalogue is also based on Hipparcos satellite observations and is likewise limited to 11th magnitude, but it includes $\sim 2,500,000$ stars. It adds density to the Hipparcos Reference Catalog, with the accuracy reduced, dependent on magnitude, to 10 - 100 mas at the epoch of 1991.25. The proper motions for the Tycho 2 Catalog were based on approximately 140 ground-based catalogs from the 20th century and have an accuracy of about 2 mas/yr. Current accuracies of about 20-100 mas per coordinate can be expected.

The UCAC is a pole-to-pole, overlapping CCD-exposure survey reaching about 16th magnitude at accuracies ranging from 15 to 100 mas, depending on magnitude, for about 100 million stars based on the Tycho 2 reference star catalog.

The FK6 Catalog is the FK5 with Hipparcos positions and quality control on the proper motions based on the different sources available (Wielen et al., 2002).

The USNO B1.0 Catalog is based on the Precise Measuring Machine (PMM) measurements of faint sky surveys, including the Palomar Sky surveys, the various Schmidt southern surveys. The result is a catalog of $\sim 1,000,000,000$ stars down to 21st magnitude with accuracies around 300 mas. It also includes proper motions and photometric magnitudes in several colors. Internal precision is about 200 mas. Systematic errors exceeding 300 mas as a function of magnitude, right ascension, and declination have recently been detected (Chesley et al., 2009). These are being investigated.

Hubble Guide Star Catalog II is a combination of first and second epoch Schmidt plates digitized at the Space Telescope Science Institute to produce positions, magnitudes, and colors to 18th magnitude for operational purposes. The epoch of observations is generally in the 1970 to 1980 period, and it is on ICRF via Tycho, but it is subject to systematic errors larger than 300 mas due to faintness.

The Two Micron All Sky Survey (2MASS) has imaged the entire sky in near-infrared J (1.25 μm), H (1.65 μm), and Ks (2.16 μm) bandpasses from Mt Hopkins, Arizona and Cerro Tololo, Chile. The 10-sigma detection levels reached 15.8, 15.1, and 14.3 magnitudes in the J, H, and Ks bands, respectively. The 2MASS data produces a point source catalog of nearly 500

million objects. The positions are accurate to approximately 80 mas at the observing epoch, but there are no proper motions for the stars. Information on 2MASS can be found at <http://www.ipac.caltech.edu/2mass>.

UCAC

The basis of the USNO CCD Astrograph Catalog (UCAC) project is an all-sky, dedicated astrometric observing program conducted by the USNO between 1998 and 2004. This survey used the USNO 8-inch Twin Astrograph's "red lens" and a 4k by 4k CCD camera from Spectral Instruments. The survey began in the Southern Hemisphere from Cerro Tololo Inter-American Observatory (CTIO) (Figure 4) and was completed at the Naval Observatory Flagstaff Station (NOFS) in Arizona. A 2-fold overlap pattern of fields was adopted with 2 exposures per field (about 25 and 125 sec exposures) to extend the dynamic range, covering 8th to 16th magnitude in a single 579 to 643 nm bandpass. The Tycho-2 Catalogue (Hoeg et al., 2000) served as the reference star catalog.

UCAC1, the first data release (Zacharias et al., 2000), provided positions for about half of the Southern Hemisphere, while UCAC2 (Zacharias et al., 2004a) gave positions and proper motions for almost 50 million stars covering declinations from -90 to about +50 deg. The proper motions were derived by combining the CCD observations with all applicable early epoch data, mainly the Astrographic Catalog (AC2000, Urban et al., 1998), about 140 other ground-based catalogs (the same catalogs used for the Tycho-2 project), and the USNO's unpublished "Yellow Sky" catalog based on PMM scans of the Northern and Southern Proper Motion Survey (NPM, SPM) plates (Girard et al., 1998, Klemola et al., 1987).



Figure 4. UCAC Observing at CTIO

Preliminary UCAC3 positions of a sample of Hipparcos stars are compared to the original Hipparcos Catalogue data (ESA 1997) and the new Hipparcos reductions (van Leeuwen, 2007). The epochs of UCAC data are between 1997 and 2004, thus providing about 10 years of epoch difference to the Hipparcos mission. The accuracy of the UCAC data is about 15 to 20 mas per coordinate for stars in the 10 to 13 magnitude range, thus allowing a significant

improvement of the proper motions for those Hipparcos stars with relatively large proper motion errors in either or both Hipparcos solutions. A subset of the sample stars are found in the Yale Parallax Catalog to allow another comparison (Zacharias et al., 2009b).

The astrometric data were reduced from the x , y data to mean right ascension, declination coordinates of the UCAC3. For these reductions over 216,000 CCD exposures were used. The 2MASS data are used extensively to probe for coordinate and coma-like systematic errors in UCAC data, such effects are mainly caused by the poor charge transfer efficiency of the 4k CCD. Errors up to about 200 mas have been corrected using complex look-up tables handling multiple dependencies derived from the residuals. Similarly, field distortions and sub-pixel phase errors have also been evaluated using the residuals with respect to 2MASS. The overall magnitude equation is derived from UCAC calibration field observations alone, independent of external catalogs. Systematic errors of positions at the UCAC observing epoch, as presented in UCAC3, are better corrected for most stars than in the previous catalogs. The Tycho-2 catalog is used to obtain final positions on the ICRF. Residuals of the Tycho-2 reference stars show a small magnitude equation (depending on declination zone) that might be inherent in the Tycho-2 catalog (Finch et al., 2010).

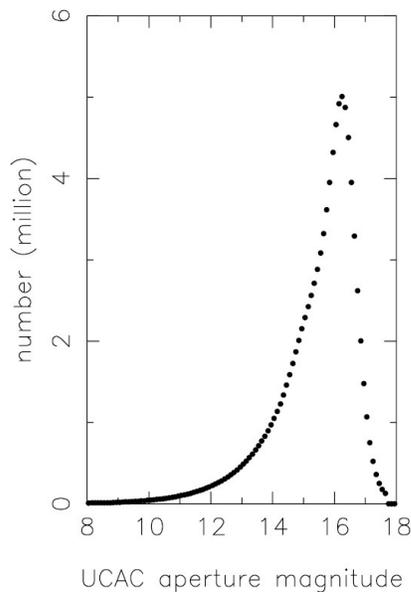


Figure 5. UCAC distribution of stars by magnitude

The UCAC3, released at the IAU General Assembly on 2009 August 10, is a highly accurate, all-sky astrometric catalog of about 100 million stars in the $R = 8-16$ magnitude range (Figures 5 and 6). Challenges in the data have been high dark current and asymmetric image profiles due to the poor charge transfer efficiency of the detector. Non-Gaussian image profile functions were explored and correlations are found for profile fit parameters with properties of the CCD frames. These were utilized to constrain the image profile fit models and adequately describe the observed point-spread function of stellar images with a minimum number of free parameters. Using an appropriate model function, blended images of double stars could be fit successfully. UCAC3 positions are derived from two-dimensional image profile fits with a five-parameter, symmetric Lorentz profile model. Internal precisions of about 5 mas per coordinate and single exposure are found, which are degraded by the atmosphere to about 10

mas. However, systematic errors exceeding 100 mas are present in the x, y data, which have been corrected in the astrometric reductions following the x, y data reduction step (Zacharias et al., 2010).

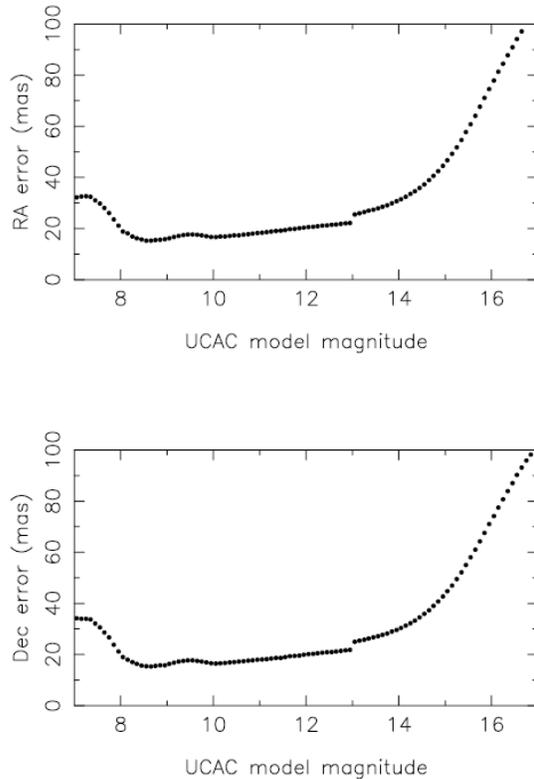


Figure 6. UCAC Central epoch position error

NOMAD

The Naval Observatory Merged Astrometric Dataset (NOMAD) is an all-sky, all-magnitudes catalog based on Hipparcos, Tycho-2, UCAC, Yellow-Sky, and USNO-B (Zacharias et al., 2004b). For each unique star, the position and proper motion data are picked from one of the input catalogs by priority, and inheriting any systematic errors of that catalog. The NOMAD astrometric data are supplemented by optical photometry data as available (mainly USNO-B from photographic plates), and the very accurate near infrared 2MASS photometry (J,H,Ks). The purpose of NOMAD is to provide “one-stop shopping” to obtain the current “best” data of any star down to about 21st magnitude. As new star catalogs become available, updated versions of NOMAD are planned, including steps toward a compiled catalog, i.e. first bring all input catalogs on a common system by removing as many systematic errors as possible, and then calculate weighted mean positions instead of just picking one source catalog. In the future NOMAD might even develop into a dynamical catalog similar to the Washington Double Star Catalog (WDS, Mason et al., 2001), where new data are added on a nightly basis as they become available.

The NOMAD version 1 has over a billion stars, with positional errors ranging from a few mas to about 300 mas at current epochs, depending mainly on the brightness of the stars. NOMAD is available at <http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/nomad>.

Ground-based Programs



Figure 7. The PS1 Telescope, deployed on the summit of Haleakala on the island of Maui, Hawaii

Today positional observational programs are primarily for the purposes of searching for near Earth objects, extrasolar planets, variability in objects, astrophysical phenomena, and other special purposes. However, these observational programs can contribute to our reference catalog sources. Ground based observations are planned by the Keck Interferometer, Large Binocular Telescope Interferometer (LBTI), Discovery Channel Telescope (DCT), Palomar Observatory Instruments, LSST, and Pan-STARRS. Very large telescopes are being designed and built, such as the VLT, GMT, and OWL. The LAMOST was dedicated in China in June, 2009. Some specific observational programs of interest are discussed below.

Large $A\Omega$

A telescope's *etendue* is defined as the product of its collecting area (A) and field of view (Ω). For many purposes, including the construction of astrometric star catalogs, large etendue telescopes may provide distinct advantages over telescopes of smaller etendue particularly for faint stars. Several telescopes designed to provide large etendue factors are currently in development. These include SkyMapper (<http://www.mso.anu.edu.au/skymapper/>), LSST (<http://www.lsst.org>), SST (<http://www.darpa.mil/tto/programs/sst/>), and Pan-STARRS (<http://pan-starrs.ifa.hawaii.edu>).

Pan-STARRS stands for Panoramic Survey Telescope & Rapid Response System. Pan-STARRS employs an innovative wide-field imaging design, and is being developed at the University of Hawaii's Institute for Astronomy. The PS1 telescope (Figure 7), currently deployed on the summit of Haleakala on the island of Maui, is a prototype for the full-up Pan-STARRS system (PS4). The PS4 system is envisioned to consist of four PS1-like telescopes working in tandem. The PS1 telescope has a field of view of 7 square degrees, and is capable of imaging about 6,000 square degrees per 8 hour night. The Pan-STARRS CCD camera is the largest digital camera ever built, with each image consisting of 1.4 billion pixels. PS1 is now in operation.

Although not specifically designed or optimized for dedicated astrometric measurements, large $A\Omega$ telescopes, such as Pan-STARRS, have the capability to make significant contributions to astrometry through rapid and repeated imaging of the sky. Owing to their large aperture, large $A\Omega$ telescopes will produce astrometric catalogs significantly deeper and more accurate than those currently available for faint stars. A single Pan-STARRS 5-sigma observation will reach magnitude 24. Co-adding multiple observations taken over many years will allow Pan-STARRS to reach magnitude 28-29. The astrometric accuracy achievable with Pan-STARRS will be demonstrated by PS1, but could be at the level of 20-70 mas, and significantly better for differential observations (such as parallaxes).

URAT

The USNO Robotic Astrometric Telescope (URAT) project is the next step beyond UCAC for the construction of a highly accurate astrometric reference star catalog going to fainter magnitudes (Zacharias, 2004, 2008, Zacharias et al., 2006). URAT will not reach the depth of the $A\Omega$ projects, instead it aims at higher positional accuracies in the 12 to 18 magnitude range. The focal plane development was sponsored by the Office of Naval Research (ONR) through a Small Business Innovation Research (SBIR) program. This resulted in the world's largest monolithic CCD manufactured by DALSA from a Semiconductor Technology Associates (STA) design (Figure 8). The chip with 10,560 by 10,560 sensitive pixels of 9 micron size was successfully manufactured in 2006, and an un-thinned, front-illuminated detector of this kind saw first light at the USNO astrograph in October 2007. For the URAT program, four of these chips will give a 28 square degree coverage on the sky in a single exposure (Figure 9 and 10) (Zacharias et al., 2007).

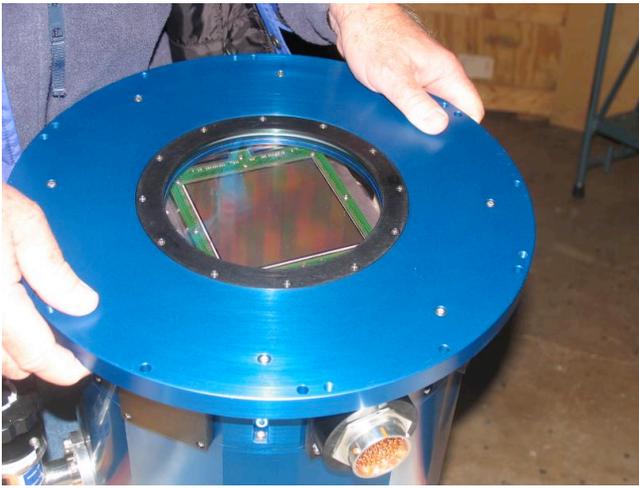


Figure 8. The largest CCD

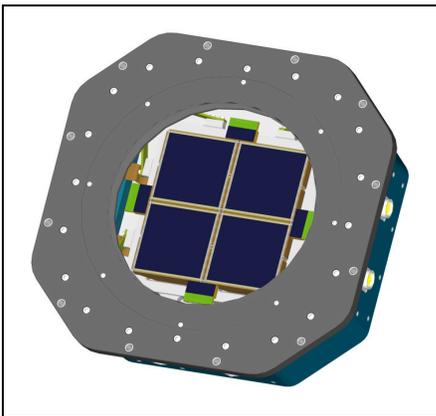


Figure 9. Mosaic Camera Head Concept- Front view



Figure 10. Dewar Head, June 2009

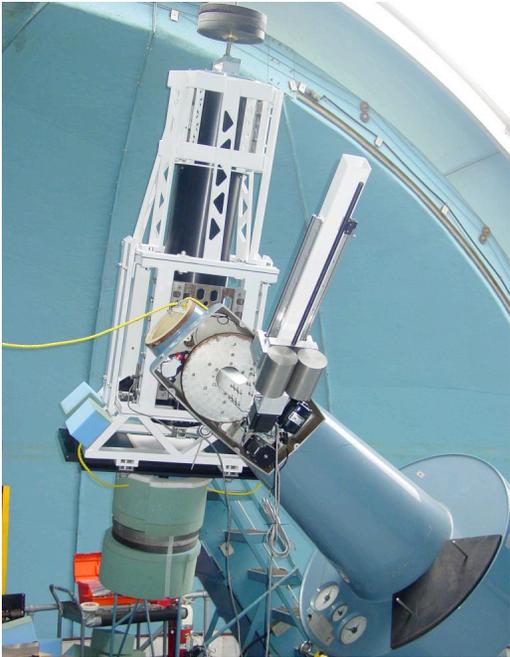


Figure 11. Astrograph May 2009 at USNO

The URAT project aims at a highly accurate (5 – 10 mas), ground-based, all-sky survey to derive positions, proper motions and parallaxes. URAT utilizes the existing, completely re-modeled USNO "redlens" 20 cm aperture astrograph with 0.905 arcsecond per pixel resolution. The URAT focal plane comprises four main CCDs and three smaller guide and focus chips in an LN2 dewar. Survey operations will be conducted from NOFS (northern) and CTIO (southern hemisphere). About 15-30 sky overlaps will be obtained from each site during 2 to 3 years of imaging to arrive at a catalog of positions, proper motions, and parallaxes for stars in

the $R = 7$ to 18 magnitude range with systematic errors expected to be smaller than those achieved by the UCAC program. Clocked anti-blooming is used to extend the dynamic range about 3 magnitudes beyond traditional saturation. Neutral density spots allow observations of naked-eye stars. URAT will provide an improved, optical, celestial reference frame, in the pre-Gaia era, linking Hipparcos stars directly to extragalactic ICRF sources, with global block-adjustment procedures playing a key role (Zacharias et al., 2009a).

Conclusion

The ICRS and ICRF should be used for all observational programs. There is no reason to continue to use the FK5 reference system, it can only degrade accuracies. The use of the CIO versus the equinox-based system is a matter of choice, but the future will undoubtedly be based on the CIO system. There are reference system catalogs available for the different magnitude ranges and the newer catalogs should be used. The UCAC 3 and NOMAD are recommended catalogs for use for space surveillance.

There is a continuing need for observations to maintain the accuracies of the reference stars and overcome the deterioration due to proper motion uncertainties. There are a significant number of new star catalogs that have relevance for space surveillance applications. In addition, owing to a number of new ground-based observatories and space-based missions, we will continue to see development of a new generation of highly accurate bright and faint star catalogs well into the next decade.

References

- Boboltz, D.A., Fey, A.L., Ouatua, W. K., Zacharias, N., Clasussen, M.J., Johnston, K.J., Gaume, R.A. (2006), "VLA Radio Star Measurement of the Rotation of the Hipparcos Frame with Respect to the ICRF", Nomenclature, Precession and New Models in Fundamental Astronomy, 26th meeting of the IAU, Joint Discussion 16, 22-23 August 2006, Prague, Czech Republic, JD16, #37
- Boboltz, D.A., Gaume, R.A. Fey, A.L., Ma, C., Gordon, D. (2010), "The Second Realization of the International Celestial Reference Frame (ICRF2) by Very Long Baseline Interferometry", BAAS, 42, 512.
- Capitaine, N., Souchay, J., Guinot, B. (1986), A non-rotating origin on the instantaneous equator - Definition, properties and use, *Celestial Mechanics*, 39, 283-307.
- Capitaine, N., Wallace, P.T., Chapront, J. (2003), Expressions for IAU 2000 Precession Quantities, *A&A*, 412, 567.
- Charlot, P., Fey, A.L., Collioud, A., Ojha, R., Boboltz, D.A. Camargo, J.I.B. (2008) "Selecting defining sources for the next ICRF based on source structure", *Proceedings of the "Journées Systèmes de Référence Spatio-temporels 2007"*. Observatoire de Paris, 17-19 September 2007. Editor: Nicole Capitaine, 8.
- Chesley, S.R., Baer, J., Monet, D.G. (2009), "Treatment of Star Catalog Biases in Asteroid Astrometric Observations", BAAS, 41, 911.
- Earth Orientation.. CEP ...<http://www.iers.org/iers/en/>
- Fey, A.L., Boboltz, D., Charlot, P., Fomalont, E., Lanyi, G., Jacobs, C., (2009), "Extending the ICRF to Higher Radio Frequencies", BAAS, 41, 676.
- Fey, A.L., Gordon, D., Jacobs, C.S., (2009), IERS Technical Note 35.

Finch, C.T., Zacharias, N., Wycoff, G.L. (2010), "UCAC3: Astrometric Reductions" *A J*, 139, 2200-2207 (2010).

Fricke, W., Schwan, H., Lederle, T., Bastian, U., Bien, R., Burkhardt, G., DuMont, B., Hering, R., Jährling, R., Jahreiß, H., Röser, S., Schwerdtfeger, H.M., Walter, H. G., (1988), *Fifth Fundamental Catalogue (FK5). Part I. The basic fundamental stars*, Veröff. Astron. Rechen-Inst. Heidelb., No. 32.

Girard, T.M. et al. (1998), "The Southern Proper Motion Program. I- Magnitude equation corrections", *AJ* 115, 855

Guinot, B. (1979). in *Time and the Earth's Rotation*, IAU Symp 82, ed D.D. McCarthy & J.D.H. Pilkington (D. Reidel Publ Co, Dordrecht), 7.

Hilton, J.L., Capitaine, N., Chapront, J. et al. (2006), "Report of the International Astronomical Union Division I Working Group on Precession and the Ecliptic", *Celestial Mechanics & Dynamical Astronomy*, 94, 351-367.

Hoeg, E. et al. (2000), *Tycho-2 Catalogue*, *A&A*, 355, L27.

IAU (1992). in *Proceedings of the twenty-first General Assembly*, ed J. Bergeron, 41.

IAU (1998). in *Proceedings of the twenty-third General Assembly*, ed J. Anderson, 40.

IAU (2001). in *Proceedings of the twenty-fourth General Assembly*, ed H. Rickman,

IAU (2006) in *Proceedings of the twenty-fifth general Assembly*, ed O. Engvold, ASP 2006.

IERS Conventions (2003). IERS technical Note 32, D. D. McCarthy & G. Petit (eds), Frankfurt am Main, Verlag des Bundesamts für Kartographie und Geodesie, 2004.

Hipparcos and Tycho Catalogues, 1997, ESA SP-1200.

IUGG (1992) *Bulletin Geodesique*, 66, 128-129.

Kaplan, G.H. (2005), *The IAU Resolutions on Astronomical Reference Systems, Time Scales, and Earth Rotation Models*, USNO Circular No 179.

Klemola et al. (1987), *Lick Northern Proper Motion program. I- Goals, organization, and methods*, *AJ* 94, 501.

Kovalevsky, J. and Seidelmann, P.K. (2004) *Fundamentals of Astrometry*, (Cambridge University Press, Cambridge).

Kovalevsky, J., Lindegren, L., Perryman, M.A.C., et al (1997). *A&A* 323, 620.

Ma, C. et al., (1997), *IERS Technical Note* 23.

Ma, C., Arias, E. F., Eubanks, T. M., Fey, A. L., Gontier, A.-M., Jacobs, C. S., Sovers, O. J., Archinal, B. A., Charlot, P. (1988), "The International Celestial Reference Frame as Realized by Very Long Baseline Interferometry", *AJ* 116, 516.

Mason, B., et al. (2001), "The 2001 US Naval Observatory Double Star CD-ROM. 1 The Washington Double Star Catalog", *AJ* 122, 3466.

Seidelmann, P.K. and Kovalevsky, J. (2002), "Application of the new concepts and definitions (ICRS, CIP, and CEO) in fundamental astronomy", *Astron & Astrophys*, 392, 341-351.

Urban, S.E. et al. (1998), "The AC 2000: The Astrographic Catalogue on the System Defined by the HIPPARCOS Catalogue", *AJ* 115, 1212.

van Leeuwen, F. (2007), "Hipparcos, the New Reduction of the Raw Data", *Astrophysics and Space Science Library*, Vol. 350.

Wielen, R., Schwan, H., Dettbarn, C., Lenhardt, H., Jahreiss, H., Jährling, R. (2002), "Sixth Catalogue of Fundamental Stars (FK6)", *VizieR On-line Data Catalog: I/264*. Originally published in: 1999VeARI..35....1W.

Zacharias, N. (2004), *Astrometric reference stars: from UCAC to URAT*, *A N* 325, 631.

Zacharias, N. (2008), "Dense optical reference frames: UCAC and URAT", Proceedings IAU Symp. 248 (Shanghai, China, October 2007): A Giant Step: From Milli- to Micro-Arcsecond Astrometry eds. Wenjing Jin, Imants Platais, Michael A.C. Perryman, Cambridge University Press, p.310.

Zacharias, N., Finch, C., Girard, T., Hambly, N., Wycoff, G., Zacharias, M. I., et al. (2010), "The Third US Naval Observatory CCD Astrograph Catalog (UCAC3)", AJ, 139, 2184-2199.

Zacharias, N., (2010), "UCAC3 Pixel Processing", A J, 139, 2208-2217.

Zacharias, N. et al. (2000), "The First US Naval Observatory CCD Astrograph Catalog", AJ 120, 2131.

Zacharias, N. et al. (2004a), "The Second US Naval Observatory Astrographic Catalog (UCAC2)", AJ 127, 3043.

Zacharias, N. et al. (2004b), "The Naval Observatory Merged Astrometric Dataset (NOMAD)", BAAS 36, 1418, abstr.#48.15

Zacharias, N., Laux, U., Rakich, A., Epps, H., (2006), "URAT: astrometric requirements and design history", Ground-based and Airborne Telescopes. Edited by Stepp, L. M.. Proceedings of the SPIE, 6267, 62670P.

Zacharias, N., Dorland, B., Bredthauer, R., Boggs, K., Bredthauer, G., Lesser, M., (2007), "Realization and application of a 111 million pixel backside-illuminated detector and camera", Focal Plane Arrays for Space Telescopes III. Edited by Grycewicz, Thomas J.; Marshall, Cheryl J.; Warren, Penny G., Proceedings of the SPIE, 6690, 669008.

Zacharias, N., Zacharias, M.I., Boboltz, D., Fey, A., Gaume, R., et al. (2008), "Extragalactic optical-radio link research at USNO", Proceedings of the "Journées Systèmes de Référence Spatio-temporels 2007. Observatoire de Paris, 17-19 September 2007. Editor: Nicole Capitaine. p.28

Zacharias, N., Wieder, G., Bredthauer, R.(2009a), "USNO Robotic Astrometric Telescope (URAT) phase 1 = U-mouse", BAAS 41, No. 1, 421.

Zacharias, N., Finch, C., Wycoff, G., Hartkopf, W. (2009b), "Improving Hipparcos Proper Motions with UCAC", AAS , DDA meeting; BAAS , 41, 910.

Zacharias, N., Finch, C., Girard, T., Hambly, N., Wycoff, G., Zacharias, M.I., et al. (2010), "The Third US Naval Observatory CCD Astrograph Catalog (UCAC3)" AJ, 139, 2184-2199.