

Optical Reference Star Catalogs for Space Surveillance: Current Status and Future Plans

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Abstract

The current status of existing star catalogs of relevance for Space Surveillance applications will be reviewed. Hipparcos and Tycho 2 provided reference stars with milliarcsecond (mas) accuracies at their epoch of 1991.25. During the 16 years since then, the proper motion uncertainties have reduced the accuracies significantly. Ground-based programs such as the USNO CCD Astrograph Catalog (UCAC) will soon provide an all-sky, astrometrically accurate (20-70 mas) reference star catalog to 16th magnitude. The USNO-B astrometric catalog contains over a billion detections, providing astrometric positions (~200 mas) and photometry for stars down to V=21 magnitude. These catalogs and others are incorporated into the Naval Observatory Merged Astrometric Dataset (NOMAD): a 100 GB dataset containing astrometric and photometric data for about 1.1 billion stars.

Numerous ground and space based programs hold the promise of providing better future astrometric star catalogs. Pan-STARRS and similar programs will image large fractions of the observable sky every clear night, producing accurate and deep astrometric catalogs. Dedicated next generation astrometric telescopes, for example the USNO Robotic Astrometric Telescope (URAT), will extend UCAC-like astrometric accuracies to fainter stars. Space-based programs like J-MAPS (brighter stars) and Gaia (fainter stars) may hold the promise of producing the highest accuracy astrometric catalogs in respective magnitude ranges.

Introduction

There have been significant improvements in the reference system and star catalogs in the last 15 years. The Fifth Fundamental Catalog (FK5) reference system and catalog has been replaced by the International Celestial Reference System (ICRS) and the Hipparcos Reference Catalog. This has improved accuracies from tenths of arcseconds to milliarcseconds.

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. 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

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

Star catalogs on the ICRF have been developed to densify and reach faint magnitudes for reference stars. However, with time the uncertainties of proper motions degrade the accuracies of the reference stars. Thus, there is a need for continuing accurate observational programs to maintain and improve the reference star accuracies.

Reference System

The ICRS is a space-fixed, barycentric astronomical reference system based on the availability of VLBI observations of distant, extragalactic, non-moving radio sources. Thus, the FK5 reference frame, based on bright, moving, nearby 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, and 2001.

Improvements in the observational accuracies and the corresponding improvements in theories have driven most of the above changes. Very Long Baseline Interferometers (VLBI) have achieved sub-milliarcsecond (mas) accuracies for observations of extragalactic radio sources. The Hipparcos and Tycho 2 Catalogues contain positions, proper motions, and parallaxes of mas or tens of mas 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 contain the acceleration of the geocenter and the gravitational potential. The BCRS is assumed to be orientated according to the ICRS axes. The BCRS and GCRS have no kinematical rotation between them, but they have different time coordinates, specifically Barycentric Coordinate Time (TCB) and Geocentric Coordinate Time (TCG), respectively.

The International Celestial Reference Frame (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 realization of the ICRF in optical wavelengths comes from the 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 the 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.

While the celestial reference frame (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, which 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 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 is a very different effect than the regular precession and nutation, is included in the new models. Free core nutation is not included in the models.

The new IAU 2006 Precession Theory was adopted in 2006 (Hilton et al., 2006). This precession theory is based on Capitaine et al. (2003). Now 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), replacing the Celestial Ephemeris Pole (CEP). It is 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.

The ERA 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 Earth Rotation Angle, 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 International Terrestrial Reference Frame (ITRF), which is a catalog of positions and velocities of point marks on the Earth. The longitude origin in the ITRF is the Terrestrial Intermediate Origin (TIO).

Based on the ICRF definition of a fixed reference frame and its realizations, there are three different moving reference systems of date being used now: one is the reference system with the precession, nutation, and constants as introduced in 1984 and the equinox based moving reference frame; a second is with improved values of precession, nutation and constants, and the equinox based moving reference frame; and the third is the new system with the CIO for the origin of the moving system, the new precession-nutation model, and the latest values for all constants.

The 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 also given in the ICRF in the fixed frame. The terminologies “equinox right ascension” 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 Earth Rotation Angle and Greenwich apparent sidereal time.

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).

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, alternative implementations are required at optical wavelengths.

The Hipparcos Reference Catalog results 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. The catalog stars without problems are the basis for the

implementation of the ICRS at optical wavelengths. At its epoch of 1991.25, this catalog is accurate to about 1 mas, but since the proper motions have about 1 mas/year uncertainties, the accuracy of the catalog is continually degrading. Current accuracies of approximately 20 mas can be expected.

The Tycho 2 Catalog is also based on Hipparcos satellite observations and is likewise limited to 11th magnitude, but it includes ~2,500,000 stars. It adds density to the Hipparcos Reference Catalog, with the accuracy reduced to about 20 mas at the epoch of 1991.25. The proper motions for the Tycho 2 Catalog were based on approximately 120 Earth-based catalogs from the 20th century. Current accuracies of about 60 mas can be expected.

The USNO CCD Astrograph Catalog (UCAC) is a pole-to-pole, overlapping CCD-exposure survey reaching about 16th magnitude at accuracies ranging from 20 to 70 mas, depending on magnitude. It contains the Hipparcos Reference Catalog and the Tycho 2 Catalog. The final catalog should be available in 2008 and should contain about 70,000,000 stars. Preliminary releases of the observational catalog are available.

The USNO B1.0 Catalog is based on the Precise Measuring Machine measurements of faint sky surveys, including the Palomar Sky surveys, the various Schmidt southern surveys, and the northern and southern proper-motion surveys. The result is a catalog of ~1,000,000,000 stars down to 21st magnitude with accuracies around 200 mas. It also includes proper motions and photometric magnitudes in several colors.

Hubble Guide Star Catalog II is a combination of first and second epoch POSS and SES plates digitized at the STScI to produce positions, proper motions, 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 due to faintness.

The Two Micron All Sky Survey (2MASS) has imaged the entire sky in near-infrared J(1.25 μ m), H(1.65 μ m), and Ks(2.16 μ m) bandpasses from Mt Hopkins, Arizona and Cerro Tololo, Chile. The 10-sigma detection levels reached 15.8, 15.1, and 14.3 mag at the J, H, and Ks bands, respectively. The 2MASS data produces a point source catalog of over 500 million objects. The positions are accurate to approximately 120 mas. Information on 2MASS can be found at <http://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 U.S. Naval Observatory 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) 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 reference star catalog.

UCAC1, the first data release (Zacharias et al., 2000) provided positions for about half of the Southern Hemisphere, while the UCAC2 second release (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 which also were used for the Tycho-2 project), and the unpublished “Yellow Sky” based on PMM scans of the Northern and Southern Proper Motion Survey (NPM, SPM) plates (Girard et al., 1998, Klemola et al., 1987). The final release, UCAC3, is in preparation. All CCD pixel data are being re-processed to provide better completeness (including fits to double stars), more faint stars, all-sky coverage, and improved astrometric and photometric accuracy. In addition, data from about 5000 photographic plates (AGK2, Hamburg and USNO Black Birch Astrograph programs) will be included to provide significantly better proper motions. Those plates were scanned on the USNO StarScan machine in Washington DC between 2000 and 2007. Re-processing of the NPM and SPM material is in preparation in a joined effort with Yale and Lick Universities. The UCAC has the most accurate positions (20-70 mas) of all currently available reference star catalogs in the 8 to 16th magnitude range, suitable for high accuracy space surveillance applications.

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. 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 is supplemented by optical photometry data as available (mainly USNO-B from photographic plates), and the very accurate near infrared 2MASS photometry (J,H,K). The purpose of NOMAD is to provide one-stop shopping to obtain the currently “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 systematic errors as much as possible, and then calculate weighted mean positions instead of just picking one source catalog. In the future this 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 200 mas at current epochs, depending mainly on the brightness of the stars.

Ground-based Programs

Observations from the ground must be made with accuracies that can contribute to current requirements. Positional observations of the types from 20 years ago are of no value. CCD cameras can achieve fainter magnitudes and better accuracies than the old photographic methods. However, just making CCD positional observations does not contribute much scientific knowledge. 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. 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. Several telescopes designed to provide large etendue factors are currently in development. These include SkyMapper (<http://msowwww.anu.edu.au/slymapper>), LSST (<http://www.lsst.org>), SST (<http://www.darpa.mil/tto/Programs/sst.htm>), 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



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

University of Hawaii's Institute for Astronomy. The PS1 telescope, 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 4 PS1-like telescopes working in tandem. The PS1 telescope has a field of view of 7 sq deg, and is capable of imaging about 6,000 sq deg 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. First light for the Pan-STARRS gigapixel camera was August 2007.

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 Ω telescopes such as Pan-STARRS will produce astrometric catalogs significantly deeper and more accurate than those currently available. 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 in the near future, but could be at the level of 20-70 mas.

URAT

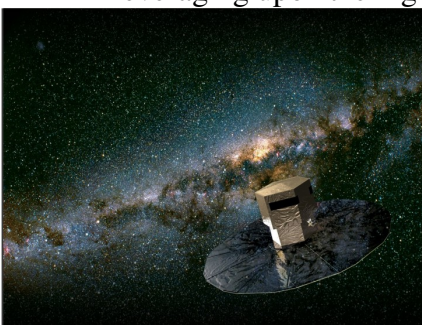
The USNO Robotic Astrometric Telescope (URAT) project is the next step beyond UCAC for the construction of a highly accurate astrometric reference star catalog going to fainter magnitudes (Zacharias, 2004, Zacharias et al., 2006). The design of the 0.85 meter aperture wide-field telescope was completed in 2005 and the primary mirror was delivered February 2008. The focal plane development was sponsored by the Office of Naval Research (ONR) through a Small Business Innovation Research (SBIR) program, resulting in the world's largest monolithic CCD manufactured by DALSA from a Semiconductor Technology Associates (STA) design. The chip with 10,560 by 10,560 sensitive pixels of 9 micron size was successfully manufactured in 2006 and a back-illuminated detector of this kind saw first light at the USNO astrograph in October 2007. For the URAT program 4 of these chips will give a 9 square degree coverage on the sky at the 0.85 meter telescope. The first phase of the URAT program ("U-mouse") will use this new focal plane at the existing astrograph to provide 27 square degrees coverage in a single exposure. The plan is to begin a new sky survey at the southern hemisphere in 2009 to provide positions, proper motions and parallaxes of stars in the 12 to 18 magnitude range with about 10 mas accuracy for the 12 to 16 mag range. Phase 2 requires more funding to complete the 0.85 meter telescope.

Space-based Programs

Despite its great success, Hipparcos remains as the world's only dedicated space astrometry mission. Several missions such as FAME and DIVA have been partially developed, then cancelled by their funding agencies. In this section we briefly discuss the prospects for three space astrometry missions: Gaia, SIM-PlanetQuest, and J-MAPS.

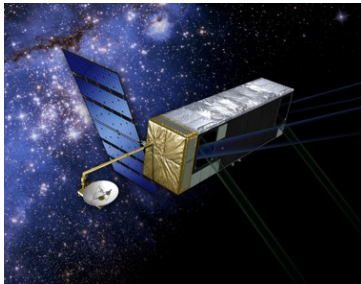
Gaia

Leveraging upon the highly successful Hipparcos satellite, Gaia is an Astrophysics driven mission which utilizes the twin field-of-view Hipparcos operations concept, updated with modern technology, to achieve significant gains in astrometric precision. Funded by the European Space Agency and



Artist's conception of Gaia

expected to launch in 2012, Gaia employs two 1.45 x 0.5 m apertures with a 35 m focal length focused on a common 106 CCD gigapixel focal plane. In addition to producing astrometric



Artist's conception of SIM-PlanetQuest

parameters for objects to 20th magnitude, Gaia will also provide photometric and a few-km/s-level radial-velocity data. The mission-end Gaia catalog, anticipated to be released in 2020, is expected to provide astrometric accuracies at the 10-25 microarcsecond level for stars brighter than 15th magnitude, and contain on the order of a billion entries. With science operations continuing for 5-6 years, the Gaia program intends to provide intermediate releases of the Gaia star catalog, perhaps at the three year mark (<http://www.rssd.esa.int/gaia>).

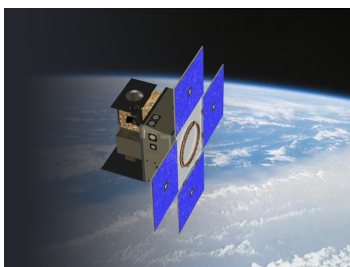
SIM PlanetQuest

SIM PlanetQuest, like Gaia, is an Astrophysics driven mission. However, unlike the Gaia survey mission, which continually and repeatedly scans the entire sky, SIM is a “pointed mission”, planned to observe a specific, relatively limited set of pre-determined celestial objects selected by the SIM Science Team and other science investigators. The mission payload is a single baseline optical interferometer, able to achieve astrometric accuracies at the level of a few microarcseconds. Given the projected mission lifetime and instrumental sensitivity, it is anticipated that the SIM star catalog will contain at most several thousand objects. Thus, the SIM star catalog, will have limited utility for general astrometric applications. SIM currently does not have a well-defined launch

date. There is no question that the SIM program has made significant progress in many key areas, including technology development. The program appears nearly ready to enter the implementation phase. However, due to limited budget resources, NASA management has decided to put the SIM on hold. The US Congress has recently directed NASA to move the SIM program into the implementation phase, but has not provided the significant amount of funding required to make this happen.

J-MAPS

The Joint Milli-Arcsecond Pathfinder Survey (J-MAPS) is a microsatellite mission intended to update Hipparcos astrometry. With its single aperture 15 cm telescope, J-MAPS



Artist's conception of J-MAPS

will access not only the brightest stars observed by Hipparcos, but also extend Hipparcos-level milliarcsecond astrometry to 15th magnitude stars. Combining J-MAPS and Hipparcos data will provide proper motion information at the level of a few 10s of microarcseconds. With a step-and-stare operations concept, J-MAPS will be capable of selecting longer dwell times for

specific fields on the sky, (unlike Hipparcos) allowing the J-MAPS star catalog to tie directly to an extragalactic reference frame. The J-MAPS program was engaged in risk reduction activities in 2006-2007, and has sufficient funding identified to proceed into the design and development stage during 2008, looking toward a 2012 launch.

A cursory look at the J-MAPS and Gaia missions might suggest significant overlap. However, the programs are quite distinct in their focus. With its smallish telescope, J-MAPS principal focus is on providing bright star astrometry. J-MAPS will be unable to observe many targets beyond $\sim 15^{\text{th}}$ magnitude. With meter-class optics, Gaia's principal focus is faint star astrometry. The Gaia focal plane detectors are expected to saturate at approximately 12^{th} magnitude, and deriving precision astrometry from saturated images has no serious heritage from either ground or space observatories. The Gaia program reportedly has plans to build channel stops into their CCDs, allowing bright star data to be derived from a small, unsaturated subset of CCD pixels, but again, this technique has no serious heritage from either ground or space.

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. There is no reason to be using either the FK5 or its generation of star catalogs, and particularly the SAO catalog should not be in use now. 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 and existing 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.

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