Star catalogs, photographic plates and errors for solar system astrometry improvements
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1 Sources of errors from plates to RA, Dec

Two major sources of errors enter at time of observation: reference star positions (random and systematic errors) and the random error from the atmosphere at the time of the observations, which scales with the inverse square root of the exposure time. There is also a dependence on field size (smaller errors for narrow fields) and aperture (smaller errors for large apertures). An error of about 20 to 40 mas can be expected for 30 arcmin wide fields, 25 sec exposure time, and small aperture telescopes (0.2 to 0.5 m), depending on seeing (Zacharias 1996). Further down the path of light, optical aberrations, distortions, and magnitude equations from the optical system (lens) need to be considered.

Assuming use of a 2-dimensional imaging detector, the most important error contributions in the plate measuring process are the optics of the machine and the mapping properties. Determining the relation between the local detector (x,y) and the global machine table (X,Y) coordinate system is the key task of the machine calibration process (Zacharias et al. 2008). Positions of stars are recorded from each individual detector image ("footprint"). Centroid positions are then converted to the global table coordinate system using the mapping model including optical distortion terms. Overlapping footprint images need to be obtained to allow the area around individual stars to fall entirely on a footprint and to allow determination of the mapping model. The optical distortion and other imperfections in this mapping process prevent the use of a single, big image file of the entire plate made up from non-overlapping, adjacent footprint images.

2 Magnitude equation and concept of reversal

Systematic errors in positions of stars as a function of magnitude ("magnitude equation") can be determined without the help of a priori known, unbiased reference stars, which are hard to come by in practice. In order to measure this systematic error, the instrument is designed to allow measurement of positions for a given star field in 2 antiparallel directions, called “direct” and “reverse”. This concept, illustrated in Fig. 1, has a long history in astrometry, for example with transit circle and astrograph observations. This principle is also applicable to the plate measuring process with the same plate being measured in direct and reverse orientation to determine the magnitude equation of the measuring machine optics. In this process the global coordinate system (X,Y), which introduces the systematic error, remains the same, while the systematic offsets in the local system (x,y) shows up doubled in an orthogonal transformation between the direct and reverse observations.

The StarScan machine at USNO, for example, displays a non-linear magnitude equation of about 0.1 μm per magnitude in its x-coordinate, while its y-coordinate is almost bias free in this respect (Zacharias et al 2008).
3 Error propagation and optimizing astrometric reductions

Whenever mapping parameters are determined from observational data, those parameters will have errors. When estimating the position of a star from such observations, the total error includes at least both the error from centroiding the star and the error propagation from the mapping model parameters. Thus positional errors in the center of a field are smallest, with increasing errors toward the edge of the field even for stars with constant centroiding errors.

This concept has extensively been analyzed by Eichhorn & Williams (1963) in the astrometric reduction step from reference stars to field star positions of on-sky observations. This concept equally well applies to the “footprint” mapping step of the plate measurement process. Furthermore, a small number of reference stars results in a least-squares fit error (“sigma”) which underestimates the true position errors of field stars when error propagation effects are not taken into account. In the extreme case (number of reference star coordinates equals the number of parameters in the mapping model) there is no "fit-error" (all residuals are zero), while the full amount of all reference star position errors propagate into the field star coordinates through the thus determined mapping model parameters.

When analyzing error contributions, it is important to keep in mind that uncorrelated random errors (Gaussian distribution) add in quadrature, i.e.

$$\sigma_{\text{total}}^2 = \sigma_1^2 + \sigma_2^2$$

Thus the total error is often dominated by a single contribution. For example, error contributions of 50 mas, 30 mas, and 21 mas add up to 62 mas, not much larger than the largest contributor of 50 mas. In order to improve the overall astrometric result significantly, one has to identify and reduce the largest single error source. Similarly, if 2 error contributions are 30 mas and 35 mas, respectively, their difference is an error contribution of 18 mas, not 5 mas.
Often the needed mapping model does include higher order terms which can not be determined sufficiently well from individual exposures or plates due to lack of number and accuracy of reference stars. However, many higher order terms such as optical distortion or tilt remain constant over a long period of time and a first round of reductions can be performed on a large number of exposures or plates by using a “best guess” for the values of the high order terms and not solve for those in the reductions. In a second step the residuals are analyzed to derive improved values of those higher order terms, which are then applied in a repeat of the reductions. Thus only the “basic” (often linear) parameters are estimated in any given least-squares fit, resulting in “benign” error propagations and thus small external errors of field star positions, while at the same time the higher order parameters in the model are used.

If parameters don’t stay constant over time, there is still a chance to minimize the mapping model fit by looking for correlations to determine parameters externally and not using them as free fit parameters. For example, the scale change of a long-focus refractor often is a function of temperature, or a plate tilt term might be correlated to the zenith distance of observations.

4 Status of reference star catalogs

The primary optical reference frame, the Hipparcos Catalogue (ESA 1997) and its extension to about 11th magnitude, the Tycho2 catalog (Høg et al 2000) are often not dense enough for solar system astrometric observations, particularly when using long-focus, small field-of-view telescopes. A good choice for an accurate, deep, reference star catalog is the recently released UCAC4 (final version of USNO CCD Astrograph Catalog), which can be accessed through CDS (Zacharias et al. 2012). It contains positions and proper motions of over 110 million stars, supplemented by 2MASS and APASS photometry. With 20 to 100 mas positional errors (depending on magnitude) at a mean epoch of 2000 and errors in proper motion of 2 to 8 mas/yr, errors of UCAC star positions at early epochs (1950 or earlier) will still be relatively large (over 100 mas).

A new all-sky astrometric survey began in April 2012, the USNO Robotic Astrometric Telescope (URAT) project. It utilizes the same “red lens” as used for UCAC but with a completely new tube assembly and a “4-shooter” camera, consisting of 4 large CCDs, each 10560 by 10560 pixels (Finch et al. 2012). This allows observation of a 10-fold sky overlap per year, with long and short exposures on each field. Proper motions and parallaxes (of nearby stars) can be derived from such observations if performed over 2 to 3 years per hemisphere. A first version of a URAT star catalog (mainly positions) is expected by the end of 2013 for the northern hemisphere with expected errors in star positions on the 10 mas level at 2013.0 mean epoch. Errors in proper motions will still be relatively large, on the few mas/yr level, even after several years of URAT observations, except for stars in the 10 to 14 magnitude range, where proper motion errors of 2 mas/yr can be expected when URAT data are combined with UCAC data.

The upcoming Gaia ESA space mission will provide basically error-free reference stars for a final reduction of solar system astrometric plates. The obtainable positional accuracy will depend on the quality of the plate material and quality of the plate measurements. The granularity of plate emulsions and emulsion shifts from the wet developing process likely introduces a limit of about 0.2 to 0.5 μm as error floor, based on StarScan experiences.
With a typical scale of 20 mas per μm of long-focus telescope data this translates to 4 to 10 mas. However, the random errors of short exposures caused by the atmosphere will likely dominate the error budget on the at least 10 to 20 mas level, with somewhat smaller errors for very narrow-angle, differential observations. We assume here good plate quality, fine gain emulsion and optimal plate measuring, else those errors will likely dominate. Thus a reference star catalog with up to about 10 mas errors (1-sigma) per star and coordinate at epoch of the observations will likely be sufficient to extract all astrometric information for such photographic plates. A plate measuring machine performing on the required level (≤ 0.2 μm) already exists at the Royal Observatory Belgium (de Cuyper et al. 2009, 2011).

ESA 1997, The Hipparcos and Tycho Catalogues, SP-1200
Eichhorn, H. & Williams, C.A. 1963, AJ 68, 221 (error propagation)
Finch, C. et al. 2012, AAS meeting 220, abstract 135.06 (URAT)
Zacharias, N. et al. 2008, PASP 120, 644 (StarScan)
Zacharias, N. et al. 2012, VizieR On-line Data Catalog: I/322 (UCAC4)