1. CURRENT ADVANCES IN ASTROMETRY

1.1 DEVELOPMENTS IN GROUND-BASED ASTROMETRIC TECHNIQUES AND LARGE CATALOGUES

CCD ASTROMETRY

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Abstract.

CCD transit telescopes are now determining star positions at faint magnitudes (i.e., down to V $\sim$ 17 mag) and with accuracies as good as $\sim \pm 150$ mas. CCD parallaxes with errors $\sim \pm 1$ mas are now being determined routinely in time periods less than 3 years.

1. Introduction

The Charge-Coupled Device (CCD) has become the detector of choice in optical astronomy because of its high quantum efficiency, linearity, and direct imaging capabilities. The growth in CCD technology has been dramatic over the past decade, and thinned 1024^2 and 2048^2 devices with excellent cosmetics are now available. The imaging area of a single device is now almost 50 by 50 mm, and work has already begun at a number of observatories on constructing large arrays of CCDs which can image over 1 deg^2 of the sky. The nature of these improvements and the bright future for CCD astrometry are the subject of this paper.

2. Wide-Angle CCD Astrometry

Several observing strategies have been developed for making CCD observations. In stare mode the telescope tracks a given star field, and the length of the exposure is controlled by the shuttering. Unfortunately, only a small amount of sky is subtended by a single typical CCD. In drift scan mode the telescope is kept stationary and the sky image is clocked across the CCD at the diurnal rate. This method enables large regions of the sky to be scanned rapidly, but is subject to several disadvantages. Namely, the exposure is controlled by the physical width of the CCD in right ascension, star

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images away from the celestial equator can be distorted by their nonuniform transits across the chip, and scanning at high declinations becomes very inefficient since the scan rate is proportional to $\cos\delta$. A third strategy, driving scan mode, overcomes the last disadvantage cited above in that the telescope is driven across the sky at a non-diurnal rate with modifications to the scan rate and direction. This latter technique will be used by the Sloan Digital Sky Survey (SDSS).

A number of telescopes employing CCD drift scanning are now being used for measuring the positions of stars, galaxies, asteroids, and comets (e.g., Gehrels *et al.* 1986, Stone and Monet 1990, and Benedict *et al.* 1991) and other instruments are either being developed or are in the planning stage. The SDSS 2.5 m telescope is nearing completion and will determine accurate star positions for about 10,000 square degree of the sky centered on the North Galactic Pole (Gunn and Knapp 1993) using an array of 30 2048^2 photometric and 17 2048 × 512 astrometric CCDs. This array will scan the sky in 2.3^o wide bands in different passbands and reach a limiting magnitude of V $\sim$ 23 mag. The targeted accuracy of the survey is ±30 mas in each coordinate.

The Flagstaff Astrometric Scanning Transit Telescope (FASTT) has been described previously (Stone and Monet 1990, Stone 1993) and has been used in making CCD observations of stars and minor planets (Stone 1994, Monet *et al.* 1994). It is a 20-cm (f/10) meridian refractor equipped with a thick front-illuminated CRAF/Cassini 1024 x 1024 (12μ pixels) and observes in drift scan mode. The limiting magnitude of the telescope is V $\sim$ 17.5 mag, and about 9000 star hr^{-1} can be observed while scanning. The best currently available reference objects are in the VLBI catalog (Ma *et al.* 1990), and the FASTT measures star positions relative to them. Since these observations are made over wide arcs in the sky, efforts have been made to reduce refractive and instrumental errors, through the use of a laser metrology system and the application of corrections for room refraction and instrumental motions. Columns 4 and 5 in Table 1 give FASTT positional errors for these observations. The increase in the errors with magnitude can be explained by Poisson statistics affecting weak star images. For well-measured objects, the positional errors are $\sigma \sim \pm 130$ mas in both coordinates. The FASTT has also been used to scan repeatedly regions in the sky at the same zenith distance. The internal error in these star positions is dominated by atmospheric errors which agree with the empirical relation given by Høg (1968). These errors are $\sigma \sim \pm 80$ mas and can only be improved by lengthening the exposure time. The remaining ±100 mas error in FASTT observations is caused by uncorrected instrumental errors.

Errors in star position can be reduced dramatically if reference objects are observed routinely in the course of scanning. Columns 2 and 3 of Table

TABLE 1. Distribution of FASTT errors.

V-Magnitude (mag)	Relative σ_x (mas)	Relative σ_y (mas)	Wide-Angle σ_x (mas)	Wide-Angle σ_y (mas)
9.0 - 9.5	±38	±35	±131	140
9.5 - 10.0	51	40	131	140
10.0 - 10.5	28	38	130	140
10.5 - 11.0	35	40	128	141
11.0 - 11.5	33	47	129	142
11.5 - 12.0	37	38	130	141
12.0 - 12.5	34	42	137	146
12.5 - 13.0	36	38	143	152
13.0 - 13.5	35	40	142	151
13.5 - 14.0	40	40	144	145
14.0 - 14.5	46	43	143	144
14.5 - 15.0	56	51	142	142
15.0 - 15.5	62	62	154	152
15.5 - 16.0	90	81	161	159
16.0 - 16.5	118	107	200	185
16.5 - 17.0	169	158	229	214
17.0 - 17.5	219	205	270	260

1 give the expected errors for this type of observing based on FASTT differential reductions. The error for well-exposed star images is $\sigma \sim \pm 38$ mas. Since program and reference objects are observed in the same field, both atmospheric and instrumental errors are greatly reduced. Unfortunately, the currently available star catalogs are neither very dense nor accurate. This situation will dramatically improve with the release of the HIPPARCOS/TYCHO catalogs. The SDSS 2.5-m telescope under construction has a 2.3^o by 2.3^o field of view, and accordingly many TYCHO stars will be observed while scanning. Simulations including atmospheric errors (Lindegren 1980, Han 1989) and errors in the TYCHO catalog have been used to compute positional errors for various field sizes and exposures. According to these simulations, a telescope with a 1^o by 1^o field of view and an exposure time of 100^s could theoretically measure star positions differentially to the TYCHO catalog at the ±11 mas level. Many existing meridian telescopes are being modernized with CCD detectors and will probably measure star positions differentially at the ±50-150 mas level. New technology telescopes, like the SDSS instrument, will do much better.

3. Narrow-Angle CCD Astrometry

The application of CCDs to ground-based, narrow-field, differential astrometric observations includes direct measures of more widely separated binary star components, speckle interferometric measures of close binary pairs, planetary satellite observations, and classical stellar trigonometric parallax determinations, of which only the latter will be discussed here. Those reporting CCD parallax measures to date include Ianna (1993), Ruiz *et al.* (1990), Tinney (1993), and the U.S. Naval Observatory (Monet *et al.* 1992). Since the first three programs employ general-user telescopes, their observational opportunities are restricted significantly. Consequently, together they have reported results for only about 20 stars and the accuracies achieved to date generally have been in the ± 2–5 mas range. The USNO program, on the other hand, has the 61-in Astrometric Reflector dedicated primarily to parallax efforts. The first USNO CCD parallaxes, obtained using a Texas Instrument 800^2 chip, were presented by Monet *et al.* (1992) and included 23 stars with precisions < 1.0 mas.

Starting in the spring of 1992, the USNO program began using a Tektronix 2048^2 CCD for parallax determinations. This device has 24 micron square pixels, providing a sampling of 0.325 arcsec/pixel and a field of view roughly 11 x 11 arcmin. Compared with limited 2.7 x 2.7 arcmin field of view presented by the TI 800^2 chip employed earlier, many more and brighter parallax targets became observable with much better quality reference star frames.

As of July 1994, 12 or more observations (126 maximum) have been obtained on each of 142 stars out of the 155 objects currently targeted. These stars have brightnesses largely in the $13 < V < 18$ range, but include a few as bright as $V \sim 12.5$ and a few as faint as $V \sim 20.5$. Preliminary reductions of this material to relative parallaxes have been carried out neglecting corrections for differential color refraction since the required photometry has not yet been obtained. The epoch ranges of the observations (i.e., time differences between the first and last observations for each star) varied from 1.06 to 2.36 years. The distribution of formal mean errors of the derived relative parallaxes is shown in Fig. 1. Clearly, a significant number of relative parallaxes (69) with precisions in the range from ± 0.4 mas to ± 1.0 mas have already been obtained with observational time spans less than 2.5 years.

Several solutions have been examined in detail in an attempt to understand why sub-mas precisions were or were not achieved. First of all, comparison of two subsets of the 142 solutions – those with epoch ranges from 1.06 to 1.42 yr (34 stars) versus those with epoch ranges from 1.85 to 2.36 yr (108 stars) – showed that the number distributions of relative par-

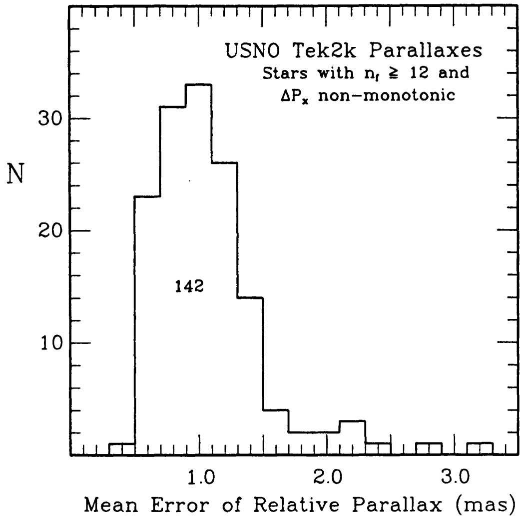

Figure 1. Distribution of formal mean errors for 142 preliminary USNO Tektronix 2048^2 CCD relative parallax solutions

allax errors were virtually the same (i.e., essentially like Fig. 1). Hence, the length of the observational series is not the major factor in producing sub-mas results. Next, the 'evolution' of solutions for ten stars was studied as data were added, one observation (CCD frame) at a time. In all instances, the error in the relative parallax decreases very rapidly for the first 10–15 observations but then decreases only very slowly thereafter. Although this behavior is roughly consistent with $\sqrt{n}$ statistical improvement, the ensemble of solutions suggests that additional factors are at play.

Detailed examination of the reference stars employed for approximately 30 fields suggests that the overall quality of the reference frame – the angular extent on the sky, the configuration with respect to the parallax star, and ability to employ well-exposed stars – is a, if not *the*, major factor in producing sub-mas results. Atmospheric turbulence is recognized as a limiting factor in differential astrometry, producing errors that scale by the angular separation to the ≈ 0.3 power and by the inverse square root of the exposure (integration) time (Lindegren 1980, Han 1989). This dependence is seen qualitatively in the present solutions; that is, fields employing reference frames of larger angular extent and requiring shorter exposure times (e.g., less than about 2 minutes) produce obviously poorer results.

The qualitative impression given by the reductions performed to date suggests that relative parallaxes with formal mean errors in the range ± 0.5 to ± 1.0 mas can readily be obtained. Just how much further improvement is possible is yet to be determined. However, the prospects for reaching

± 0.3 mas for fields with optimal reference star configurations and for reasonable observational times intervals (e.g., < 5 yr) seems at least possible at this juncture. Astrophysical problems that can only be addressed directly by parallaxes with precisions ≤ 0.5 mas include: 1) the distance to F–G subdwarfs of varying metallicity for calibration of the distances to globular clusters; 2) the delineation of interior composition loci within the degenerate star sequence; and 3) accurate determinations of the luminosities of a sample of dwarf carbon stars to clarify the nature of the components of these supposedly binary systems. CCD parallaxes for the F–G subdwarfs will require a technique for magnitude compensation (i.e., for selectively dimming the bright target star while simultaneously exposing on faint reference stars). A neutral density spot (3 mm in diameter, deposited on an optically flat quartz substrate, and producing 6.0 magnitudes of attenuation) has been ordered and tests using it will start this fall.

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