RECENT ADVANCES WITH THE USNO (FLAGSTAFF) TRANSIT TELESCOPE

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ABSTRACT. The Flagstaff Astrometric Scanning Transit Telescope (FASTT) has been equipped with a new CCD detector, and further improvements in instrumentation have been made. An evaluation of its performance indicates that the telescope can determine accurate star positions, tied into the VLBI/VLA extragalactic reference frame, for stars as faint as V $\sim$ 17.5 mag. With further improvements, it is hoped this accuracy can be improved. A special scanning technique for stars at high declinations has been developed that allows scanning up to the pole. Positions tied into the extragalactic reference frame for FK5 and radio stars have been determined with the FASTT, and a comparison of these positions with their catalog values is given.

1. Program Development

The FASTT telescope has been previously described in Stone and Monet (1990) and in Harris *et al.* (1991). It is a 20-cm (f/10) meridian refractor with a scale of 99 arcsec mm^{-2}. The Texas Instruments 800 x 800 thinned CCD has been replaced with a CRAF/Cassini 1024 x 1024 (12μ pixels) thick front illuminated CCD which is cooled with a closed-cycle helium refrigerator to about -100°C. The refrigerator eliminates the need to use a liquid coolant for cooling the CCD. The passband is defined with a WF/PC F606W filter which gives a bandwidth of 4700 - 7300Å. The circle reading system has been upgraded with the CCD-TV cameras described in Stone, Monet, and Bird (1991) which are accurate at the $\pm$0.01 arcsec level. The dominant source of error in reading the FASTT Heidenhahn circle is caused by errors in the division corrections which are about 5 times larger. The clock system consists of two Cesium beams and two sidereal converters. Twenty RTD temperature probes have been installed at various locations within the FASTT pavilion and on the telescope and are being used to collect nightly temperature data which is used in modelling refraction and instrumental motions. Atmospheric refraction is computed with the numerical methods discussed in Stone (1984), and a correction for room refraction within the FASTT pavilion can also be made. A laser interferometer has recently been installed that enables instrumental motions in azimuth at the $\pm$0.01 arcsec level to be monitored in real-time. Moreover, the setting

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of the FASTT has been automated with a compumotor drive system, and the real-time position of the telescope is determined with a laser shaft encoder.

Algorithms for the rapid processing of digital data (finding stellar images and fitting two-dimensional Gaussians to subrasters centered on them) have been completed. Nightly reductions of data are now automatically done in batch mode after the completion of each observing session. Eventually, most of the reductions will be done in real-time, eliminating the need to save pixel data. The recent addition of a Silicon Graphics IRIS 4D/340S computer will greatly reduce the amount of image processing time needed which can be quite sizable considering the FASTT can typically observe about 9000 stars per hour when observing in scan mode. A DEC 5000/200 workstation is used to control the CCD, and a DEC micro-VAX II computer is used to control the telescope and to gather environmental data.

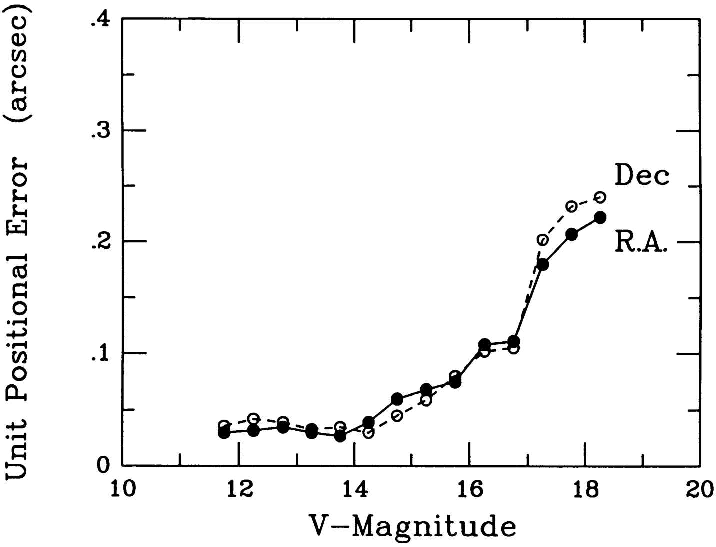

Fig. 1 - The internal positional accuracy of the FASTT CRAF/Cassini CCD. The results in both coordinates agree very well with one another.

Two different scanning techniques are used with the FASTT telescope. Normal scanning is when a star is clocked across the CCD (see Gehrels 1991 for a review of different CCD scanning methods) at the sidereal rate. The length of an exposure is set by the width of the CCD which is 81 secδ seconds of time for the FASTT. Normally scanned FASTT images at high declinations $\delta > 70°$ are badly distorted by the circular motion of stars around the pole, and these images are considered unmeasurable. Another scanning technique, partial scanning, has been developed specifically for scanning at high declination which is very effective. The resulting star images are very round. The method consists of opening the shutter for a predetermined amount of time (81 seconds adopted for the FASTT), scanning at the sidereal rate, closing the shutter, and then rapidly reading out the CCD. With this method, $n(1 - \cos\delta)$ columns of the chip, where n is the width of the CCD in pixels, will be uniformly exposed. This part of the CCD image is usable, and the size of this area increases with the declination. At high declinations, stars can be observed several times in the course of their meridian transits because of their slow motions across the chip. Partial scan images even at $\delta = 89°$ are very round and measurable. With a combination of normal and partial scanning, the FASTT can scan the sky from the equator to the pole.

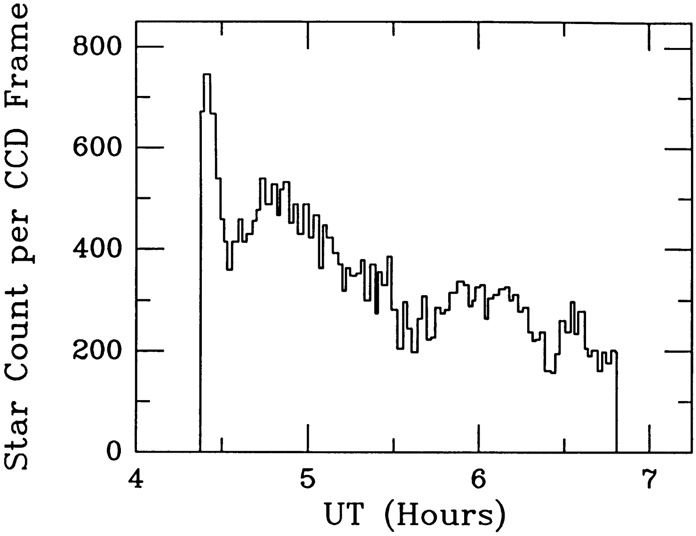

Fig. 2 - The number of stars observed with the FASTT as a function of time. The scan lasted 2.5 hours. The scan started near the Galactic equator and extended to higher Galactic latitudes, hence, the decrease in the number of stars observed.

2. Accuracy of Star Positions

Several different methods have been used to determine the accuracy of the FASTT. In order to determine the inherent accuracy of the CRAF/Cassini CCD, several fields with known very accurate photometry were scanned repeatedly on different nights. Each night's observation for a given field was reduced to a common coordinate system by applying corrections for zero-point, scale, and the orientation of the chip on the sky. For each field, the dispersions of the relative star positions were determined and plotted against magnitude. The results for the various fields agreed very well with one another, and Figure 1 show a typical plot. The internal accuracy is ±0.05 arcsec for a single relative star position ($V < 15$ mag) and about ±0.2 arcsec for the faintest measurable stars. The limiting magnitude of the FASTT is $V \sim 17.5$ mag, and the brightest observable stars have magnitudes $V \sim 10$ mag. Brighter stars are saturated in their cores and are not measured in FASTT observing programs. The in-

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crease in the positional errors with increasing magnitude is largely governed by Poisson statistics. Fainter stars have decreased countrates, and consequently, noise caused by the sky background and the CCD readout becomes increasingly important. Figure 2 illustrates the large amount of data that can be rapidly observed with the FASTT. On the average, about 9000 stars per hour can be observed, and with a larger CCD (e.g. 2048 x 2048 pixels) this amount would be even larger.

The above accuracies only indicate the inherent accuracy of the CRAF/Cassini CCD. In determining equatorial star positions, other sources of errors, such as caused by uncorrected instrumental motions and anomalous refraction, are also important. Equatorial star positions and their associated unit errors have been determined by first determining instrumental star positions from the clock, CCD, and circle readings and then transforming these positions into the VLBI/VLA J2000 extragalactic reference frame. Each night, 10 to 15 extragalactic reference objects, taken from the Argue *et al.* (1984) catalog, are observed with the FASTT. The observations for these reference objects are used to transform the instrumental positions to the extragalactic reference frame with equations of condition similar to those given by Requieme and Mazurier (1991). Errors in position can be determined by comparing FASTT optical positions with the radio positions of extragalactic objects with known accurate positions.

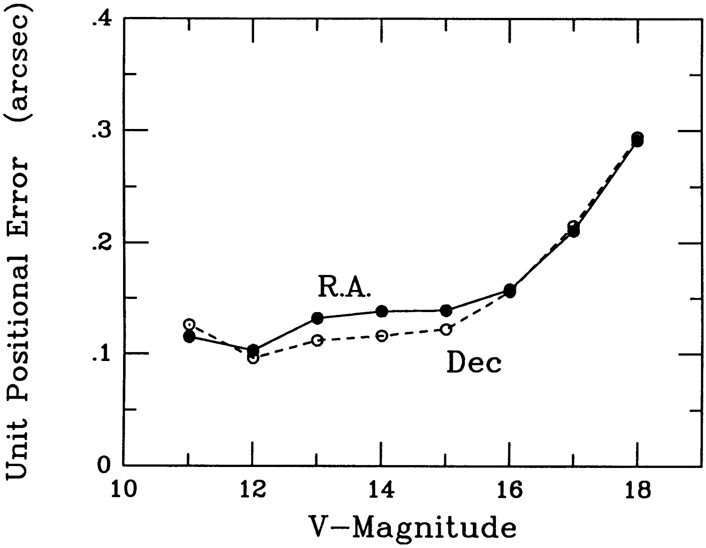

Fig. 3 - The accuracy of equatorial positions determined with the FASTT. The results for each coordinate agree with one another.

Errors can also be determined by comparing positions determined on different nights. The two methods give similar results as illustrated in Figure 3. The shape of the error curve is similar to that shown in Figure 1. As seen, stars brighter than V < 15 mag are accurate at the ±0.12 arcsec level in both coordinates for a single observation. The errors for the fainter stars are larger.

Multiple observations of stars will reduce these errors further. Repeated strip scans at differing zenith distances (ZD) suggest the limitation in accuracy imposed by the atmosphere at Flagstaff is about ±0.08 secZD arcsec in right ascension and ±0.09 secZD arcsec in declination for a single observation. There is some indication that these limitations are worse on nights of poor seeing. The FASTT positional errors are approaching the limit set by the atmosphere.

In the course of observing with the FASTT, regions with photometric standards are also observed. The standards are given by Landolt (1973) and Graham (1982). Instrumental magnitudes are first formed from the FASTT photometric readings and then reduced to magnitudes in the manner discussed in Hardie (1962). The accuracy of the FASTT magnitudes is ±0.05 mag. These magnitudes can be reduced to the Johnson V-passband by adding the color term .361(B-V) to them once the colors of stars become known.

3. Observations Made With the FASTT

Besides the instrumental development program, several observing programs are being conducted with the FASTT. For about a year, observations of FK5, radio stars, and QSO's have been made. Optical positions for FK5 and radio stars can be determined with the FASTT that are directly tied into the VLBI/VLA extragalactic reference frame in the manner discussed above. The declinations of these stars range from δ = -30° to 65°, and the magnitudes of the brighter FK5 stars were reduced by 6.2 magnitudes by placing a wire screen in front of the objective. From a sample of 90 FK5 stars, global differences between the FASTT and catalog (in the sense extragalactic - FK5) are found to be

$$\Delta\alpha \cos\delta = -0.019 \pm 0.018 \text{ (s.e.) arcsec} \qquad \Delta\delta = -0.013 \pm 0.018 \text{ (s.e.) arcsec}$$

Similarly, the global differences between the FASTT and radio positions for 15 radio stars are found to be

$$\Delta\alpha \cos\delta = -0.049 \pm 0.036 \text{ (s.e.) arcsec} \qquad \Delta\delta = -0.015 \pm 0.041 \text{ (s.e.) arcsec.}$$

Offsets between the optical and radio positions of extragalactic objects can be computed by comparing the FASTT optical positions with the known radio positions. All objects were taken from the Argue *et al.* (1984) catalog, and in all, there were 46 objects. There were no significant differences between the offsets in right ascension and declination, and the magnitude of the mean offset in each coordinate was found to be 0.07 ± 0.05 (s.e.) arcsec. Some of the offsets are large and significant when compared with their errors. Six offsets exceeded 0.2 arcsec, and of these six, four were radio galaxies. Since there were only six radio galaxies within the entire sample of 46 objects, this result suggests that radio galaxies are probably not good objects for defining an extragalactic reference system because significant offsets between their optical and radio emissions can be present. Fortunately, the vast majority of objects in the Argue *et al.* catalog are either QSO's or BL Lac objects whose offsets are, with few exceptions, small with respect to their errors. In compiling the Argue *et al.* catalog, radio galaxies were chosen in regions where suitable QSO's or BL Lac objects could not be found.

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