CCD OBSERVATIONS OF PLANETS AND ASTEROIDS IN THE EXTRAGALACTIC REFERENCE FRAME

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Abstract. This paper describes the methods used with the Flagstaff 20–cm CCD transit telescope for determining the positions of planets and asteroids directly in the extragalactic reference frame. As a result, the observations are not affected by (optical – radio) zonal errors, which can be ±0.1 arcsec or greater in catalogs based on traditional fundamental observations. The telescope can observe objects as faint as V $\sim$ 17.5 mag with an accuracy of $\sigma \sim \pm 0.16$ arcsec in each coordinate. As a result, a large number of asteroids and the planets Uranus, Neptune, and Pluto are being routinely observed so that their ephemerides can be improved, masses determined, and accurate predictions made for occultation events. These observations are considerably more accurate than most previous results.

1. Introduction

The Flagstaff Astrometric Scanning Transit Telescope (FASTT) is an automated 20–cm (f/10) meridian telescope equipped with a Cassini 1024^2 charge-coupled-device (CCD) detector with 12μ pixels and filtered passband $\lambda\lambda 4700$ – 7300Å. All FASTT positions are determined in the extragalactic reference frame from ancillary observations of radio reference objects (Johnston *et al.*, 1995) observed each night, and the limiting magnitude of the telescope is V $\sim$ 17.5 mag. In the reductions, provisional equatorial positions (α, δ) are first formed for both the observed radio reference and program objects. Since the radio positions $(\alpha_{radio}, \delta_{radio})$ are known also for the reference sources, the two coordinate systems can be related with the following equations

$$(\alpha - \alpha_{radio}) \cos\delta = c_1 + c_2 \sin\delta + c_3 \cos\delta + c_4 t \sin\delta + c_5 t + c_6 t^2 + c_7 t \cos\delta \quad (1)$$

$$\delta - \delta_{radio} = c_1^{'} + c_2^{'} \tan\ ZD + c_3^{'} t + c_4^{'} t^2 + c_5^{'} \sin\ ZD \quad (2)$$

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where ZD is the zenith distance of the object being observed, and t is the time of the observation. The first three terms in Eq. (1) are Bessel's terms, scaled by $\cos\delta$, and the time-dependent terms in the equation were determined empirically to be sometimes important in FASTT reductions. The terms in Eq. (2) allow for a zero-point difference, scale errors in refraction and flexure, and temporal changes of the FASTT. After the transformation coefficients in these equations are determined, these equations can be then used to transform all the provisional coordinates to J2000 equatorial coordinates in the extragalactic reference system. About 25 radio reference sources are observed each night with the FASTT. The telescope and reductions are more fully described by Stone *et al.* (1996).

Most positions for solar system objects have been determined traditionally from differential reductions using standard reference star catalogs, such as the GSC, AGK3, and SAO, whose errors at modern epoch range from $\sigma \sim \pm 0.4$ to ± 1.5 arcsec. Consequently, errors in ephemerides of ± 0.5 arcsec are not uncommon. To be sure, there are more accurate reference star catalogs, but unfortunately, they are not very dense. Some of the brighter objects ($V < 10$ mag) have been observed in meridian telescope programs at greater accuracy. All of these observations have been referenced to the optical reference frame, currently defined by the FK5 catalog, which has systematic errors that can be as large as ± 0.1 arcsec according to early Hipparcos data (Lindegren *et al.*, 1995). Since all FASTT observations are tied into the extragalactic reference system, the resulting positions are not affected by these errors. Moreover, instrumental errors in FASTT positions are known to be small, and the overall accuracy of FASTT positions has been determined to be ± 0.16 arcsec for a single observation (Stone *et al.*, 1996). Because of the good accuracy (both systematically and internally) and ability to reach faint magnitudes, the FASTT is well suited for many observing projects. This paper discusses recent FASTT observations of solar system objects.

2. Observations of Asteroids and Planets

2.1. ASTEROIDS

The solar system objects observed by the FASTT in the extragalactic reference frame consists of asteroids targeted for spacecraft missions, asteroids for mass determinations, objects for occultation events, and the outer planets Uranus, Neptune, and Pluto. Most of these programs were started in 1994 and are continuing. Table 1 presents a representative sample of these objects along with the accuracy of the individual FASTT observations and the selective observing program, where *Galileo* and *NEAR* are for the respective spacecraft flyby missions, *Mass* is for the program of determining

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TABLE 1. FASTT planet and asteroid positional errors for a single observation.

Object	$\sigma_\alpha \cos\delta$ [″]	σ_δ [″]	Project
951 Gaspra	±0.11	±0.21	*Galileo*
243 Ida	0.16	0.21	*Galileo*
253 Mathilde	0.15	0.17	*NEAR*
433 Eros	0.18	0.19	*NEAR*
197 Arete	0.06	0.07	*Mass*
1313 Berna	0.22	0.26	*Mass*
45 Eugenia	0.08	0.13	*Mass*
468 Lina	0.14	0.14	*Mass*
348 May	0.15	0.20	*Mass*
Uranus	0.24	0.24	*Orbit*
Neptune	0.23	0.24	*Orbit*
Pluto	0.14	0.15	*Orbit*
Mean Error	±0.15	±0.18	

the masses of asteroids, and *Orbit* is for improving the ephemerides of the outer planets. As seen, there is little difference in accuracy among the various programs in the table, and the mean of these errors are $\sigma \sim \pm 0.15$ and ± 0.18 arcsec, respectively in right ascension and declination.

Starting in 1991, the FASTT began determining positions for the asteroids 951 Gaspra and 243 Ida prior to their encounters with the *Galileo* spacecraft, respectively, in 1991 and 1993. As seen in the table, the FASTT positions were quite accurate. Furthermore, comparisons between these positions and the final JPL ephemerides for these asteroids showed no obvious systematic differences (Yeomans *et al.*, 1993; and Monet *et al.* 1994). These and other observations were very important for achieving successful encounters with both of these asteroids (Yeomans *et al.*, 1993). Currently, the FASTT is supporting the NEAR spacecraft mission by making observations of the asteroids 243 Mathilde and 433 Eros. FASTT observations of these objects started in 1994 and will continue up to their respective spacecraft encounters in 1997 and 1999. Figure 1 shows (Observed – Calculated) differences between FASTT observations obtained in 1995 and a recent JPL ephemeris for the asteroid 433 Eros. As seen, there is good agreement between the observed and predicted positions, and the scatter in the plots is about $\sigma \sim \pm 0.18$ arcsec. A similar result was obtained for 243 Mathilde in 1995 (see Table 1). Observations made in 1996 for 243 Mathilde have been

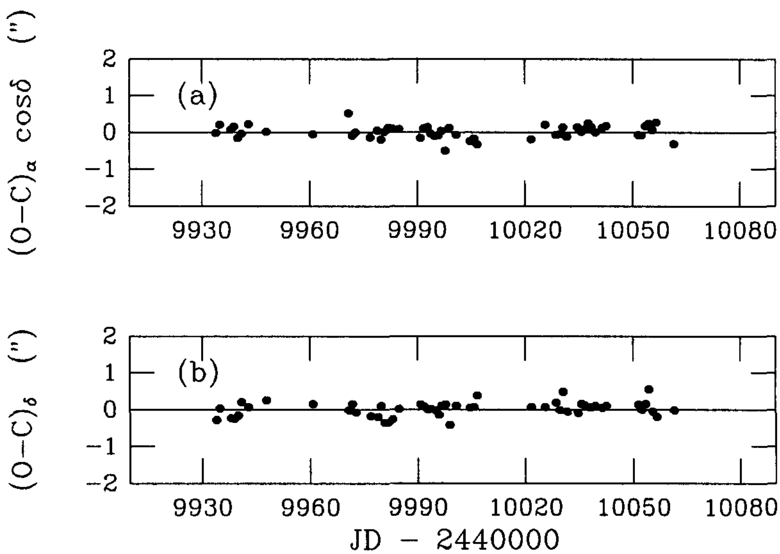

Figure 1. Residual differences in the sense (FASTT observed − JPL ephemeris) are shown in right ascension and declination for observations of the asteroid 433 Eros made in 1995 with the FASTT. There is little evidence for systematics, and the scatter in the plots is $\sigma \sim \pm 0.18$ arcsec.

just completed. Hopefully, these and other observations will contribute to a successful *NEAR* mission.

FASTT observations of asteroids are also being used to determine the masses of selective asteroids. In this program, asteroids have been chosen that have had a close enough encounter with another asteroid so that their masses can be determined from a perturbation analysis. These encounter can last for decades, and in general, observations made over many years are needed for a good mass determination. Each month, a list of asteroids is supplied by J. Hilton (Hilton *et al.*, 1996) for observation, and a representative sample of these objects are listed in Table 1. There are many asteroids in the program. The FASTT observations are particularly important for this project, since they are typically 3-times more accurate than previous observations, and many observations can be obtained at a recent epoch. The first results of this program will be available soon, wherein the mass of 15 Eunomia has been determined from perturbations caused by the asteroids 1284 Latvia and 1313 Berna (Hilton, 1996).

2.2. OCCULTATIONS

The FASTT is also determining the positions of stars that might be occulted by asteroids, planets, or the satellites of planets. Data from occultations are needed to determine the physical sizes and shapes of asteroids and to investigate the atmospheres of planets and their satellites. Often, the prediction for an occultation is poor, because the position of the candidate star is not very well known. The positions for many of these stars are frequently taken from standard catalogs, such as the GSC, PPM, or SAO, which are only accurate to $\sigma \sim \pm 0.3$ arcsec or worse. Differential reductions using astrographic plates can reduce these errors; but nonetheless, accuracies of $\sigma = \pm 0.1$ arcsec are hard to achieve which unfortunately is often needed for making a good occultation prediction. For several years the FASTT has been observing occultation candidate stars, reaching an accuracy of $\sigma \sim \pm 0.05$ arcsec with typically 10 observations. In many cases, observations are made of both the candidate star and asteroid that might occult it over an extended period of time, wherein instrumental and refractive errors can be largely eliminated in differential reductions. Predictions made from FASTT observations have contributed to several successfully observed occultations, including 654 Zelinda, 85 Io, and Triton. A post-analysis of these events indicates the FASTT positions were accurate at the 1-σ level.

2.3. PLANETS

As discussed by Standish *et al.* (1995), there is a continuing need for optically determined positions for the outer planets in order to improve their ephemerides. In particular, the ephemeris for Pluto needs improvement, since the planet has been only observed over a quarter of its orbit and most observations are only accurate to ± 0.5 arcsec. Since 1995, the FASTT has been determining the positions of Uranus, Neptune, and Pluto in the extragalactic reference frame, and the first results are discussed in Stone (1996), where FASTT observations are compared with the recent DE403 ephemerides discussed by Standish *et al.* (1995). In general, there is very good agreement between the FASTT observations and DE403 predictions. With one exception, systematic differences are under 0.06 arcsec and not significantly larger than their formal errors. Moreover, the scatter in the residuals (see Table 1) ranges from $\sigma = \pm 0.14$ to ± 0.24 arcsec. For example, Figure 2 shows the (Observed – DE403) residual differences for Neptune observed in 1995 with the FASTT. In both coordinates, there is good agreement between the observed and predicted planetary positions. The exception pertains to the declination of Pluto, where an (Observed – DE403) difference of $\Delta\delta = 0.13 \pm 0.03$ (s.e.) arcsec was found, which is statistically significant. This difference could be caused by zonal errors in the fundamental reference system, or alternately, the DE403 ephemeris for Pluto might need revision and a runoff for Pluto in declination is being seen. Future observation of Pluto are being made for clarification.

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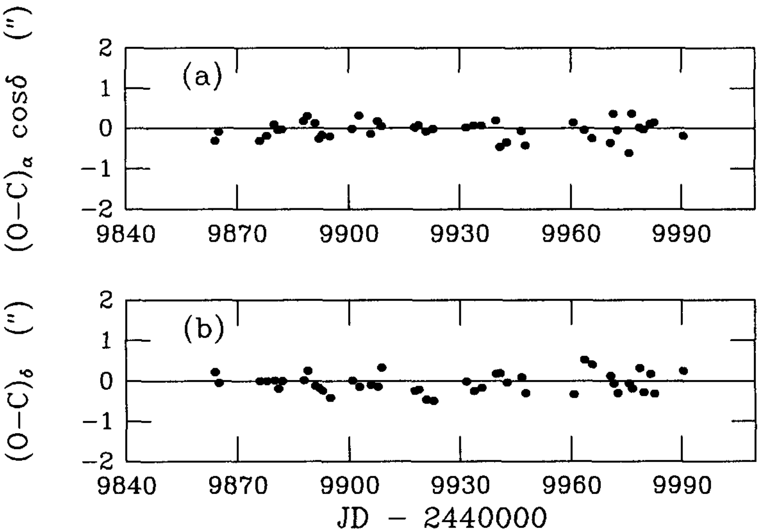

Figure 2. Similar to Figure 1 but showing (FASTT – DE403 ephemeris) residual differences for observations made in 1995 of Neptune.

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