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SPECKLE INTERFEROMETRY AT THE US NAVAL OBSERVATORY. X.

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ABSTRACT

The results of 3047 speckle interferometric observations of double stars, made with the 26 inch (66 cm) refractor of the US Naval Observatory, are presented. Each speckle interferometric observation of a system represents a combination of over a thousand short-exposure images. These observations are averaged into 1572 mean relative positions and range in separation from 0.″20 to 62.″86, with a median separation of 4.″19. This is the 10th in a series of papers presenting measures obtained with this system and covers the period 2003 January 13 through 2003 December 1. Included in these data are nine older measures whose positions were previously deemed possibly aberrant but are no longer classified this way following a confirming observation. Four of these systems have new orbital elements, which are presented here as well.

Key words: binaries: general — binaries: visual — techniques: interferometric

Online material: machine-readable tables

1. INTRODUCTION

From 2003 January 13 through 2003 December 1, the 26 inch (66 cm) refractor of the US Naval Observatory was used on 95 of 253 scheduled nights (38%). The remaining nights were lost to marginal weather conditions. Not all nights were scheduled, as a consequence of either instrumental difficulties or the camera's being removed for other observing projects or runs. Further details describing the techniques and methodology of speckle interferometry are contained in the earlier papers in this series and references therein (most recently, Mason et al. 2004).

While individual nightly totals varied substantially (from four to 78 objects per night), these nights together yielded 3047 observations (pointings of the telescope) and 2594 resolutions (double stars resolved and measured). After removing marginal observations, calibration data, and tests, a total of 2182 measures remained, which have been grouped into 1572 mean positions. Included in these are 115 confirmations of binaries with only one previous observation. While some of these are relatively recent discoveries of the *Hipparcos* or Tycho instruments (ESA 1997), some have remained unconfirmed for quite a while. Also included in these data are nine observations with the same USNO speckle camera system from 2002. These measures were not published in Mason et al. (2004), as they were significantly different from previous observations or orbital predictions; however, they have now been confirmed with new measures obtained in 2003. Some of these discrepancies reflect the prematurity of earlier orbit calculations; for four of these systems we were able to obtain new elements that, although still preliminary, allow for better ephemerides to be published. For the other five, while there are certainly consistent residual trends that demonstrate systematic runoff, these data are not sufficient to justify a new orbital calculation.

2. OBSERVING LISTS AND CALIBRATION

The observing list was constructed using the same methodology discussed in Mason et al. (2004). The majority of the systems were those that are considered neglected (the last date of observation was 10 or more years ago) or doubles needing confirmation. Additional sets were added. These sets included objects with uncertain motion, definitive orbits used to characterize errors, those with expected rapid motion, bright ($V < 5$) stars used for navigation, and others. Absolute calibration is determined by the use of a slit mask placed at the objective end of the telescope. Observation of a single star through this mask produces interference fringes that can then be used to determine spatial and angular calibration independently of any errors associated with using even "definitive" binaries.[2]

3. RESULTS

While speckle interferometry has made significant progress in the discovery of new companions, or the first resolution of companions detected by other techniques, the pairs are frequently quite closely separated, often under 100 mas. Given the modest aperture of the USNO telescope, it is certainly not ideal for the discovery of close companions, although it has confirmed the duplicity of many close binaries first detected from space.

Table 1 presents coordinates and magnitude information from CDS[3] for those binaries that are resolved for the first time. These three systems were found as additional components to known pairs. Column (1) gives the coordinates of the primary of the pair. Column (2) is the discoverer designation, the WSI (Washington Speckle Interferometry) number (note that since all three are additional components of known doubles, they are designated "AC"). Column (3) gives the estimated visual magnitude of the primary, and column (4) the estimated visual magnitude of the component discovered here. Column (5) gives notes indicating the circumstance of the discovery. The mean double star positions (T, θ, and ρ) of these systems (all were observed two or more times) are given in Table 2.

Table 2 presents the mean relative positions of the members of 1406 systems having no orbital determination. The first two

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[1] Science and Engineering Apprenticeship Program (SEAP) intern.

[2] See http://ad.usno.navy.mil/wds/orb6/orb6c.html for more information.

[3] Magnitude information is from the Aladin sky atlas, operated at CDS, Strasbourg, France.

TABLE 1

New WSI Pairs

Coordinates α, δ (2000) (1)	Discoverer Designation (2)	Mag$_{\text{primary}}$ (est.) (3)	Mag$_{\text{new}}$ (est.) (4)	Note (5)
06 07 48.4, +38 36 58..........	WSI 32 AC	11.9	13.5	1
19 20 33.0, +35 11 09..........	WSI 33 AC	6.3	11.5	2
21 55 18.7, +44 13 18..........	WSI 34 AC	10.9	12.0	3

Notes.—(1) Serendipitously found while examining J 906. (2) Serendipitously found while examining HAU 24. (3) Serendipitously found while examining BRT 1154. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

columns identify the system by providing the epoch 2000 coordinates and discoverer designation. The next three columns give the epoch of observation (expressed as fractional Besselian year), the position angle (in degrees), and the separation (in seconds of arc). Note that the position angle has not been corrected for precession and is thus based on the equinox for the epoch of observation. Objects whose measures are of lower quality are indicated by colons following the position angle and separation. These lower quality observations may be due to one or more of the following: close separation, large Δm, one or both components very faint, a large zenith distance, and poor seeing or transparency. They are included primarily because of either the confirming nature of the observation or the number of years since the last measured position. The sixth column indicates the number of observations contained in the mean, and the seventh flags any notes. While the sixth column reflects the number of measures, each measure represents the combination of over 1000 short-exposure images, from which a single measure is obtained in autocorrelation space. The most common note indicators are either "C," indicating a confirming observation, "L," indicating that the system is being analyzed for linear motion, or a number (N) indicating the number of years since the system was last measured. This is only given for systems with $N \geq 50$ yr. One hundred fifteen systems are here confirmed. Since priority is given both to unconfirmed systems and to systems not observed recently, the time since last observation can be surprisingly large; for the systems in Table 2, the average time since the last observation is 25 years. Two hundred fifty-six have not been observed in the last 50 years or more, and 21 have not been observed in 100 years or more, with the maximum being 111 years for BRT 2491 (Barton 1939). Of those confirmed, 48 are relatively recent: four from *Hipparcos* (ESA 1997), 40 from Tycho (Høg et al. 2000a, 2000b; Mason et al. 2000; Fabricius et al. 2002), and four discovered with the USNO speckle system (Mason et al. 1999b, 2001, 2002, 2004) on either the USNO 26 inch or the McDonald 2.1 m. Of the 1406 measures in Table 2 (i.e., systems without orbits), the median separation is 9″.0.

This median separation is much greater than is typically obtained by high-resolution techniques. In many of these cases, the camera is functioning more as a fast-readout ICCD imager than a classical speckle interferometer. These wider (and therefore less optimal) systems were observed for typically one of three reasons: (1) to investigate the calibration parameters and repeatability of results outside the r_0 window (the typical isoplanatic patch); (2) to gather data on rectilinear systems that are currently under investigation (Hartkopf et al. 2004); and (3) bright stars were observed, which are most useful for navigation purposes. One hundred fifty-three of the systems in Table 2 have an "L" code in the notes column. These are pairs for which linear elements have been determined. A complete analysis of all linear systems is currently in preparation (Hartkopf et al. 2004). While a few of these may indeed be orbit systems (with extremely long periods, high-eccentricity orbits near apastron, or both), most are likely optical doubles. Morphologically, the images of wide binaries of similar brightness exhibit the same sort of pattern as if the isoplanatic patch were considerably wider than conventional wisdom states. A more thorough analysis of this will be done following completion of the Linear Elements Catalog of Hartkopf et al. (2004).

Table 3 presents the mean relative positions for 166 double star systems with published orbital determinations. The first six columns are identical to the corresponding columns of Table 2. Columns (7) and (8) give $O-C$ orbit residuals (in θ and ρ) to the orbit referenced in column (9). Notes are designated in column (10). The objects in Table 3 tend to be more frequently observed, closer pairs than those in Table 2, with a median separation of 0″.94 and a mean time interval since last observation of 1.4 yr. Wider orbit systems were also observed, but only a few ($N = 14$) had separations greater than 4″.0. While many objects have more than one observation generating a mean position, eight objects have motion that is rapid enough to make listing individual measures appropriate. For systems with corrected elements, which are presented in Table 5 below, residuals are provided for the new calculation as well as the best of the historical determinations. When more than one historical orbit of approximately equal value is known, both sets of residuals are provided. Figure 1 presents a plot of ρ versus Δm for the systems in Tables 2 and 3 with separation less than 2″.5, plus others observed but not resolved during the calendar year.

TABLE 2

Speckle Interferometric Measurements of Double Stars

WDS Designation α, δ (2000)	Discoverer Designation	Epoch (2000+)	θ (deg)	ρ (arcsec)	n	Notes
00026+6606	STF 3053 AB	3.770	70.2	15.01	3	
00031+3033	MLB 591	3.860	334.5:	5.69:	2	C, 75
00047+3416	STF 3056 AB-C	3.804	2.9	25.85	1	L
00048−0952	HU 100	3.815	345.2	4.02	1	
00052+4514	BU 9001 AC	3.766	235.3	21.12	1	

Notes.—(C) Confirming observation. (L) Linear elements determined (see Hartkopf et al. 2004). (1) Has a published orbit, but elements are incomplete. See http://ad.usno.navy.mil/wds/orb6.html. (2) See also Table 1. (3) Measure published in Mason et al. (2004) corrected. (4) See Table 4, note 5. (5) See Table 4, note 6. ($N = 50 - 181$) Number of years since last measure. Table 2 is presented its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

TABLE 3

Speckle Interferometric Measurements and Residuals to Systems with Orbits

WDS Designation α, δ (2000) (1)	Discoverer Designation (2)	Epoch (2000+) (3)	θ (deg) (4)	ρ (arcsec) (5)	n (6)	$O-C$ (deg) (7)	$O-C$ (arcsec) (8)	Reference (9)	Notes (10)
00014+3937	HLD 60	3.774	171.6	1.26	2	−0.9	0.05	Heintz 1963	
00063+5826	STF 3062	3.831	335.5	1.50	2	0.3	−0.03	Söderhjelm 1999	
00093+7943	STF 2	3.831	18.8	0.78	3	1.0	−0.04	Heintz 1997	
00162+7657	STF 13	3.831	51.5	0.92	3	0.0	0.02	Olević & Jovanović 2001	
00184+4401	GRB 34 AB	3.804	63.3	34.93	1	−1.1	−0.37	Lippincott 1972	

Notes.—(*) System used in characterizing errors. (1) This measure was inconsistent with previous measures and so was not included in Mason et al. (2004). However, available data are deemed insufficient for a new orbital calculation at this time. (2) This system was expected to show significant motion over the calendar year, so multiple observations have been obtained. (3) Appears to be approaching periastron sooner than expected, and with a more eccentric orbit. The new orbit is listed in Table 5, ephemerides based on these elements are listed in Table 6, and the orbit is illustrated in Fig. 1. (4) This measure was inconsistent with previous measures and so not was included in Mason et al. (2001). The new orbit is listed in Table 5, ephemerides based on these elements are listed in Table 6, and the orbit is illustrated in Fig. 1. Table 3 is presented in its entirety in the the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

Table 4 presents systems that were observed but not detected. In some cases, a binary that is not resolved may be detected by asymmetries in the autocorrelation. This usually occurs when the Δm is large and ρ is small. Given the most recent observational data, it was expected that these pairs should have been resolved; however, they were not. Possible reasons include orbital or differential proper motion making the binary too close or too wide to resolve, a larger than expected Δm, incorrect pointing, and misprints or errors in the original reporting paper. It is hoped that reporting these will encourage other double star astronomers to either provide corrections to USNO or to verify the lack of detection. While many are quite old and their lack of detection may be due to unknown proper-motion drift, some are recent and so should

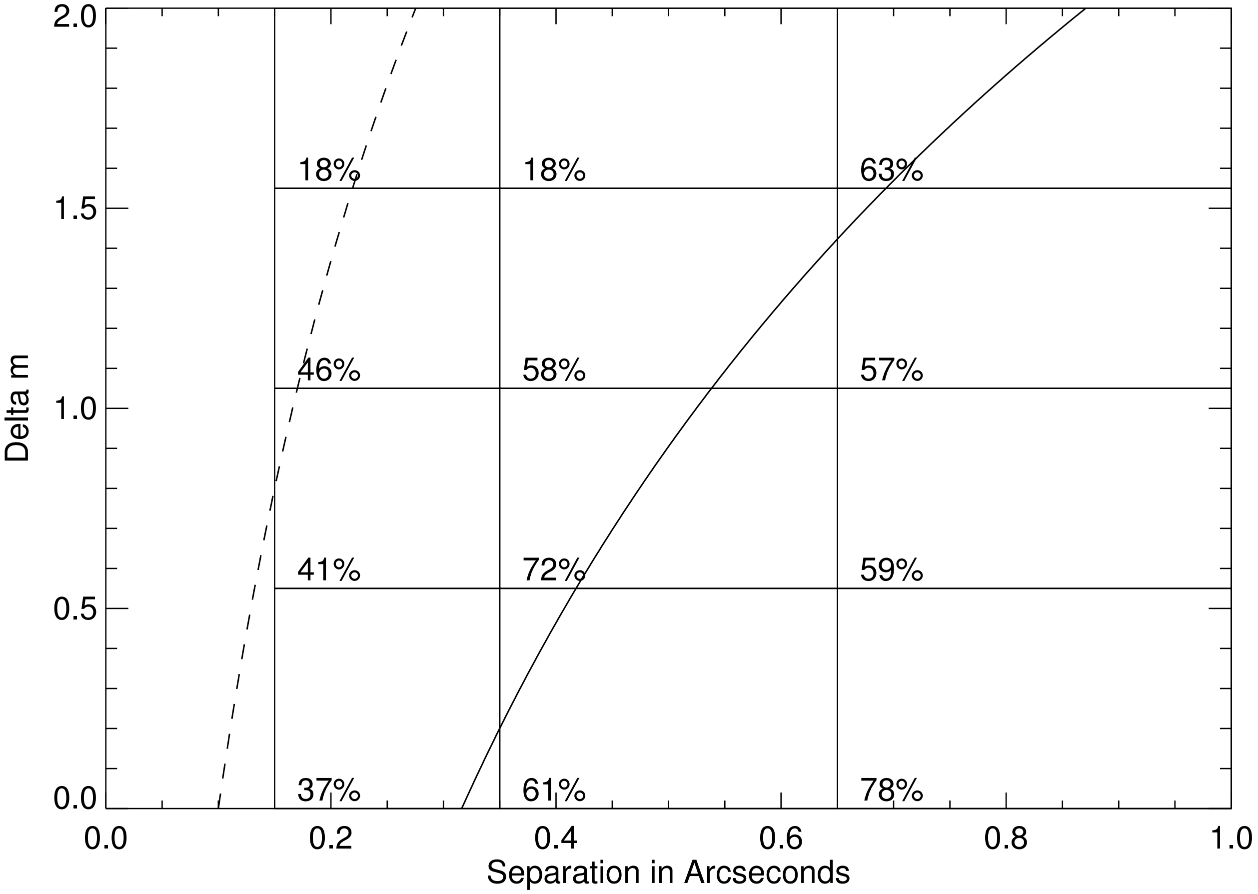

Fig. 1.—Success rates for different bins in ρ-Δm space from 2003 USNO 26 inch speckle data. Membership in the bins is based on the WDS Δm value and the last measured separation. The errors of each bin are based on Poisson statistics. Placement in these bins makes no allowance for doubles whose positions have radically changed or whose Δm is radically different, or for unconfirmed doubles that are erroneous. The curved lines indicate the measure-of-difficulty relationship of Öpik (1924) as modified by Heintz (1978). The Δm-ρ combinations to the right of the solid line are considered completely known. Those to the left of the dashed line are considered virtually unknown. Systems at greater than 2″.5 with a Δm of up to 4 are all in the Öpik "completely known" space and have success rates of better than 95%.

TABLE 4

BINARIES NOT FOUND

COORDINATE α, δ (2000)	DISCOVERER DESIGNATION	OBSERVATION Date	P.A. (θ)	Separation (ρ)	PUBLISHED MAGNITUDE Primary	Secondary	NOTE
00298+2345	TDS 1490	1991	128	2.3	11.4	12.0	
00473−1407	TDS 1612	1991	27	2.4	10.8	11.2	
01286−1349	BRT 1837	1902	85	2.4	10.9	11.6	
02073+4330	TDS 2123	1991	113	4.6	11.3	11.9	
02131+3724	TDS 2162	1991	239	2.5	11.4	12.0	
02450−0135	OL 9	1918	331	2.6	9.5	10.5	1
04035+7320	TDS 124	1991	239	1.6	10.8	11.6	
04053+7306	TDS 127	1991	258	1.6	10.6	11.6	
04121+2332	POU 422	1891	52	4.7	9.4	10.0	2
04481+7810	TDS 148	1991	200	1.3	10.7	11.1	
04483+8223	TDS 2969	1991	91	2.0	11.2	11.9	
07172+0250	BAL 2264	1910	354	1.6	9.7	11.2	3
07158+0131	TDS 4642	1991	288	1.4	9.9	11.9	
18262+0435	TDT 866	1991	28	1.5	10.6	11.3	
18400+1146..................	TDT 984	1991	137	1.4	10.6	11.9	
18413+1002	TDT 996	1991	45	1.8	10.5	11.8	
19090+2739	L 44	1907	173	4.5	8.7	9.7	4
19267−1557	STN 46	1933	195	4.9	6.8	7.3	5
19590+2953	L 31	1927	130	3.4	9.0	9.5	6
21091+2434	SLE 533	1982	43	3.4	11.0	11.9	
21093+0618	TDT 2789	1991	20	2.0	10.2	11.6	
21144+0807..................	TDT 2847	1991	255	1.9	10.8	11.7	
21156+0419..................	TDT 2865	1991	111	2.3	11.1	11.5	
21353+3043	TDT 3047	1991	19	2.4	11.2	12.5	
22169+6154	TDT 3441	1991	254	1.7	10.9	12.0	
22140+6132	TDT 3416	1991	347	2.4	10.8	11.9	
23070+4920	TDT 3892	1991	134	2.8	11.2	12.3	

NOTES.—(1) Measured twice by Olivier (1909, 1920) but not seen by any other observer. (2) Only arcminute coordinates are available for this pair resolved by Pourteau (1933). Because of this, it is not certain that the right star was observed. (3) Listed as having two measures in the WDS (Baillaud 1943; Urban et al. 1998); however, they are two different measures of the same plate and, possibly, the same plate defect. Not seen since. (4) Two early 20th-century measures (Lewis 1907; Bowyer 1907) are of a fairly wide system and are quoted here. There is a recent measure by Argue et al. (1992; 57°.0 and 0″.69), which, if real, may explain the lack of resolution by the system's being slow-moving and too close at present. (5) STN 46 appears to be the same as S 716 with an error in right ascension. See Table 2, note 4. (6) Measures from Lewis (1899, 1901) were assigned to both this pair and 20010+2956 (L 32) in the Burnham (1906; BDS 9785 and BDS 9824) and Aitken (1932; ADS 13233 and ADS 13255) catalogs. Published coordinates and magnitudes are also similar, and only one pair is seen on POSS plates, leading to the conclusion that these are the same system. The L 32 designation was maintained, as its WDS designation was correct. See Table 2, note 5.

not show significant differential motion. In addition to the 39 Tycho double stars that were confirmed in Table 2, 19 were not detected and thus are presented in Table 4.

4. ANALYSIS

As mentioned in § 2, absolute calibration is determined by means of a slit mask placed in front of the primary. Since absolute calibration is done in this manner, binaries with well-characterized motion can be used to approximate errors. Binaries on the calibration orbit list were again selected. Twenty-seven of the objects listed in Table 3 fall into this category, two of which (STF 1937 and STF 1523) have motions over the calendar year that are significant enough that multiple observations are listed in the table. For the following error analysis, mean residuals of these two systems are determined. For all 27 systems, the mean residuals in position angle and separation are −0°.15 ± 1°.42 and −0″.00 ± 0″.04, respectively. The nonzero mean position angle residual is most likely reflective of the accuracy of the observer lining up the plumb bob for calibration. The separation residual was examined in several separation regimes to check for any systematic errors with calibration systems close to the resolution limit or for systems outside the typical r_0 patch. For separations of 0″.2–1″, 1″–2″, 2″–4″, and 4″–12″.5 the residuals in separation are −0″.01, 0″.01, 0″.2, and −0″.04, respectively, all with standard deviations between 0″.02 and 0″.05. At closer separations, small absolute errors result in larger relative errors. In the same four bins the errors are −2.08%, 0.54%, 0.72%, and −0.62%. The errors in the separate bins are more reflective of the quality of the individual orbits and are, therefore, not adequate for the investigation of second-order errors. If only grade 1 orbits are used for calibration, the absolute separation standard deviation decreases; however, the relative value increases. This, though, is due more to grade 1 orbits being quite close (of the nine grade 1 orbits, seven have semimajor axes less than 1″) rather than an investigation of their applicability for error analysis. Using calibration systems for error characterization seems valid; however, they are not adequate for the examination of smaller factors. Given the errors in the orbits, and assuming they are random, it is advisable to observe as many of these as possible. Also, there does not seem to be any gross problem with using wider systems for this investigation.

Finally, Table 5 presents the new, calculated orbits. All were determined in the method described in Seymour et al. (2002) using the observation-weighting rules of Hartkopf et al. (2001). The orbit grade change is, as expected, minimal: from 0.2 to

TABLE 5

New Orbital Elements

WDS Designation α, δ (2000)	Discoverer Designation	P (yr)	a (arcsec)	i (deg)	Ω (deg)	T_0 (yr)	e	ω (deg)	Grade[a]
11190+1416	STF 1527	318	2.201	63.4	181.2	2012.2	0.861	23.6	4
18250+2724	STT 2315 AB	2094	2.062	107.6	127.7	1982.0	0.6877	352.4	4
18443+3940	STF 2382 AB	1725	4.17	118.6	198.0	190	0.243	198	4
23176−0131	BU 79 AB	302	1.32	123.6	172.8	2112	0.451	303	4

[a] For an explanation of orbit grading, see Hartkopf et al. (2001).

1.0 grades. Most of these systems, with the possibly exception of STF 1527, are of the "Is this orbit really necessary?" type. Indeed, that one may be as well, although it is approaching periastron and is certainly worth monitoring. It is hoped that highlighting it here will serve to put it on other high angular resolution programs. Its separation is expected to be less than 0″5 for the next 15 years, and over that time the position angle is predicted to change by 172°! For the other three systems, were there not earlier calculations it would probably be advisable to wait. However, all of these are beginning to show systematic runoff, which resulted in their earlier USNO speckle measures being unpublished. The orbital elements listed in Table 5 and illustrated in Figure 2 are, while better than the previously published orbits, probably not terribly reliable over the course of a complete orbit. However, the ephemerides in Table 6 should be quite adequate for the next decade. Indeed, it

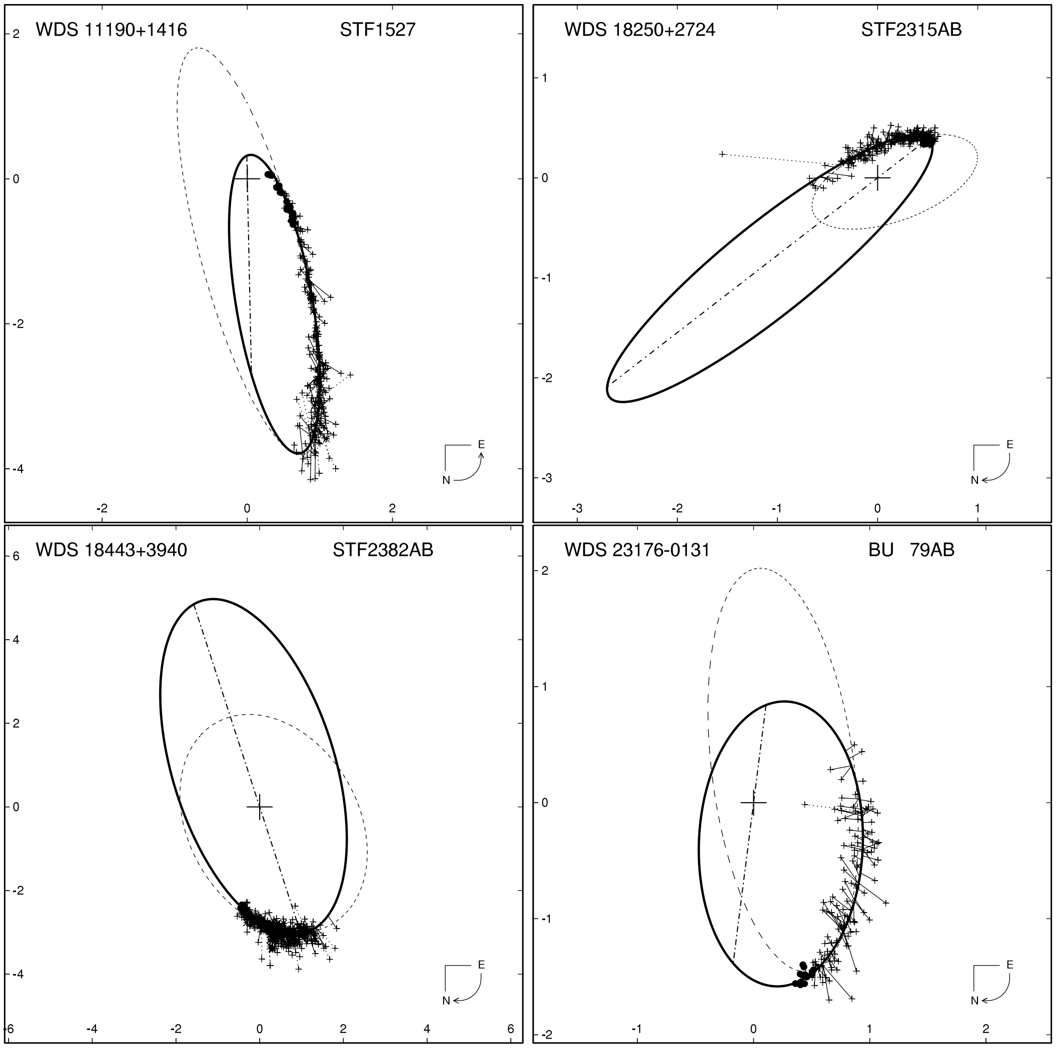

Fig. 2.—Relative visual orbits for WDS 1190+1416, 18250+2724, 18443+3940, and 23176−0131; the x and y scales are in arcseconds. The solid curves represent the newly determined orbital elements, while the dashed curves represent previously published orbital elements. The previous calculations are cited in Popović & Pavlović (1995; 11190+1416), Heintz (1960; 18250+2724), Güntzel-Lingner (1956; 18443+3940), and Heintz (1962; 23176−0131). The dot-dashed lines indicate the line of nodes. Interferometric measures are shown as filled circles, and visual measures as plus signs. All measures are connected to their predicted positions on the new orbit by "$O-C$" lines, where dotted $O-C$ lines indicate measures given zero weight in the final solution. The direction of motion is indicated on the north-east orientation in the lower right of each plot.

TABLE 6
Ephemerides for Binaries with New Orbital Elements

WDS Designation α, δ (2000)	Discoverer Designation	2004		2006		2008		2010		2012	
		θ (deg)	ρ (arcsec)	θ (deg)	ρ (arcsec)	θ (deg)	ρ (arcsec)	θ (deg)	ρ (arcsec)	θ (deg)	ρ (arcsec)
11190+1416	STF 1527	98.4	0.365	119.4	0.330	142.8	0.327	165.2	0.337	189.1	0.295
18250+2724	STT 2315 AB	121.6	0.639	120.8	0.635	120.0	0.631	119.2	0.627	118.3	0.622
18443+3940	STF 2382 AB	349.3	2.432	348.8	2.416	348.2	2.399	347.6	2.383	347.0	2.366
23176−0131	BU 79 AB	13.9	1.591	13.1	1.594	12.3	1.597	11.4	1.599	10.6	1.601

might be said that the greatest use of the elements from Table 5 is for position determination for dates not given in Table 6. Using the orbit-grading precepts of Hartkopf et al. (2001), the grades of the new calculations are provided in Table 5 as well. All but one of these would be classified subjectively as preliminary or indeterminate. Nevertheless, the average orbit grade improvement is over half a grade. Relative visual orbits of each system are plotted in Figure 2, with the x- and y-axes indicating the scale in arcseconds. The solid curves represent the newly determined orbital elements of Table 5, while the dashed curves represent the previously published orbit cited in the figure legend.

Maintenance of a telescope and building dating from the late 19th century is always a challenge and continues to be handled with remarkable expertise by the USNO instrument shop. Thanks are extended to John Pohlman, Tie Siemers, David Smith, and Gary Wieder.

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