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SPECKLE INTERFEROMETRY AT THE U.S. NAVAL OBSERVATORY. XXI.

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ABSTRACT

The results of 2408 intensified CCD observations of double stars, made with the 26 inch refractor of the U.S. Naval Observatory, are presented. Each observation of a system represents a combination of over 2000 short-exposure images. These observations are averaged into 1602 mean relative positions and range in separation from 1.″94 to 107.″41, with a median separation of 11.″96. This is the twenty-first in this series of papers and covers the period from 2015 January 13 through 2015 December 19. Significant instrumentation changes are reported in this paper.

Key words: binaries: general – binaries: visual

Supporting material: machine-readable table

1. INTRODUCTION

This is the twenty-first in a series of papers from the U.S. Naval Observatory's speckle interferometry program, presenting results of observations obtained at the USNO 26 inch telescope in Washington, DC (see, most recently, Hartkopf & Mason 2015). Over 26,000 mean positions have now resulted from this program since its inception by Charles Worley, Geoff Douglass, and colleagues in the early 1990s (see Douglass et al. 1997). Due to the limited resolution capability of the 26″ refractor, few fast moving systems are accessible, so the primary goal of the program has been the observation of pairs that could be characterized as neglected, that is, unconfirmed or not observed in approximately a decade. To that end 15,750 different pairs have been observed.

From 2015 January 13 through 2015 December 19, the 26 inch telescope was used on 67 of 240 (28%) scheduled nights. While most nights were lost due to weather conditions, time was also lost due to testing and upgrades to instrumentation and software, other mechanical or software issues, and to a lack of observing personnel.

Most of the systems observed with this camera have separations well beyond the regime in which there is any expectation of isoplanicity, so we classify the observing technique for all of these measures as just "CCD astrometry," rather than speckle interferometry. Despite this classification, there is an expectation that the resulting measurements have smaller errors than classical long focus CCD astrometry due to the much larger number of correlations and the exposure time being less than τ_0, the atmospheric coherence time. Each measurement is the result of many hundreds of correlations per frame, and up to several thousand frames per observation. This ensemble of observations is processed and measured using the conventional directed vector autocorrelation techniques used by the CHARA and USNO speckle teams for over 20 years. See, for example, other papers in this series or in the CHARA Speckle series.[5]

[5] Hartkopf et al. (2000) is the most recent publication in this not yet concluded series.

Individual nightly totals varied substantially, from 3 to 100 observations per night (mean 35.9). The results yielded 2408 observations and 2471 resolutions. Observation of multiple star systems in a single CCD field gives the somewhat non-intuitive result where the number of resolutions exceeds the number of observations. After removing marginal observations, calibration data, tests, and "questionable measures" a total of 2228 measurements remained. These "questionable measures" are not all of inferior quality but may represent significant differences from the last measure, often made many decades ago. Before these measures are published they will need to be confirmed in a new observing season to account for any possible pointing or other identification problems. The tabulated list of these is retained internally and forms a "high priority observing list" for subsequent observing seasons. In this continuing process, we here also present one measure from 2011 and one from 2012. These 2230 measures were grouped into 1608 mean relative positions.

Observing list construction remains the same as described for the "secondary" camera in Mason et al. (2007). The calibration procedures, including the empirical correction for closer pairs, are described in Hartkopf & Mason (2015). This method also allowed us to use double stars to evaluate the observing system accuracy by the observation of pairs with well-characterized orbital or linear solutions. Evaluation of the ensemble of tabulated O−C values allows the error to be grossly characterized as $\pm 1.^{\circ}0$ in position angle and $\pm 1\%\rho$ in separation. The average O–C of $-0.^{\circ}1$ and $+0\%\rho$ is consistent with a data set that has no systematic effects.

2. INSTRUMENTATION

The last major upgrade to the 26 inch was performed in the early 1960s, under the direction of Mikesell (1968), which included adding a synchro system to display the pointing of the telescope, upgrading the right ascension clamp, adding a new tailpiece for the telescope tube as well as a new diaphragm and grating system in front of the objective, a new console, new motors, wiring, and electronics. Over the years since that upgrade, some components have been changed and patches made to the electronics, which were poorly documented. One of us (Rafferty) initiated a pre-retirement project to build new electronics where possible and install new wiring. In that way, the telescope could continue to be operated with the old console, electronics, and wiring, and testing could be done on new electronics and wiring without taking the telescope out of service for long periods of time.

2.1. 2003-4 Upgrades

The 2003-4 upgrades involved replacing the right ascension clamp, console, most of the motors, and all the wiring and electronics.

The electronics layout followed a similar approach for nearly all the functions of the floor, dome, and telescope they control. All the switches and buttons on both the console and hand block control were changed to 5VDC, which in turn control solid-state relays located in the chassis in the electronics rack located outside the dome. These solid-state relays were activated with a voltage range of 3VDC to 32VDC. It was hoped that using these similar, low-voltage, solid-state relays would make automating the telescope under computer control at some later date easier. The solid-state relays switch 110VAC to latching, two-contact, or three-contact mechanical relays. Latching relays are used for functions that can be controlled from different locations using momentary switches, where the status of the function is determined by the state of the latching relay and not the position of the switch. The mechanical relays control 5VDC, 24VDC, or 110VAC depending on the function involved. Each function has another set of electronics located near the motors, clutches, motor controls, and limit switches involved. For example, the electronics controlling the declination clamp and slow-motion were mounted on the side of the telescope tube. The electronics controlling the right ascension slew-motion motor were mounted inside the telescope pier.

2.2. Computer Control of the 26 Inch

Following GB's successful work on the URAT telescope (Zacharias et al. 2015) a contract was let for both him and Rafferty to begin the process of computer control of the 26″ telescope. The initial task consisted of building interface electronics between the computer and the electronics built during the 2003–4 upgrades, and to build safeguards so the telescope could not be damaged if the computer lost control of the telescope. The interface electronics involved a series of mechanical relays that would allow the telescope to be operated either manually or under computer control. These safeguard electronics were only activated when the telescope was under computer control. The safeguards ensured that the computer could not operate the telescope unless the floor was completely down, and motors for moving the telescope would be turned off if the telescope pointed below the horizon (using Mercury switches) or if the back end of the telescope came close to hitting the pier of the mount (using limit switches on both the R.A. and Decl. axes). All of these safeguards could be activated independently of the computer. Computer models were implemented that took into account the offset from the center of the dome due to the German equatorial mount of the 26″ and painstaking nights were spent pointing the telescope as well as synchronizing the positioning of the dome slit. The final software product included controls for a new CCD for the finder[6] as well as several other pieces of hardware not yet brought online (see Section 2.3 below). The computer control was ready for initial testing in mid-summer 2014 with finder camera testing initiated in autumn 2014. Testing of computer control of the telescope continued, but the inclinometers and the Galil motion controllers remained tempermental through the end of 2014. Pointing model testing was initiated in 2015 February and computer control operation was initiated on 2015 June 22. Initially, it consisted of working both outside and inside the dome, utilizing both computer control and the 1960s synchros to point and verify pointing.

In summer 2015 one of us (Ragan) began to develop a higher level program, utilizing the subroutines of GB for pointing and to generate an accurate pointing model. By June 29, the weather station[7] and spycam[8] were operational and observing was moved out of the dome. Variable flexure of the very long (32 foot) tube presented considerable difficulty and the smaller field of view of the CCD on the finder (approximately 30% that of the eyepiece) posed challenges; however, an initial empirical pointing model was developed on July 23 and by September routine observing (i.e., not testing) was initiated. Following the successful use of the pointing model, the offset corrections were implemented in the higher level control program December 7. At present, the observing target routinely falls in the field of view of the finder camera, provided the target is within a few hours of the meridian. An evaluation of observing efficiency comparing 2015 October with 2013 September found a 25% increase in objects per hour due to faster pointing, automated dome motion, and no use of the elevating floor. Subjective results in 2016 suggest that this is a lower limit. This does not take into account increased total throughput due to decreased observer fatigue in non-temperate observing conditions.

2.3. Future Improvements

Instrumental improvements with the 26″ continue and will be implemented through 2016 and into the future. These include the following.

1. The camera design in use at present is a very-wide-field-of-view simple-lens system designed by A. Tokovinin (CTIO). We are implementing automated lens switching to enable higher magnification to explore closer, faster moving, and more astrophysically interesting systems. This will be done with the object being in the same focus and found at the same location on the speckle ICCD. This was implemented in spring 2016 with subsequent exploration of the curious scaling issues for close pairs addressed empirically in Hartkopf & Mason (2015). The magnification of these two different implementations are 1261× and 297×, giving fields of view of approximately 25″ and 100″, respectively. See Figure 1.

    With this instrumental improvement, closer pairs will be accessible. Furthermore, it will also be possible to return to the preferred calibration methodology of using a slit-mask to generate fringes from single stars to determine scale values through the full optical chain, independent of known or calculated double star parameters.

[6] SBIG Model STF-8300M.

[7] Davis 6163.

[8] Axis P1353 Network Camera.

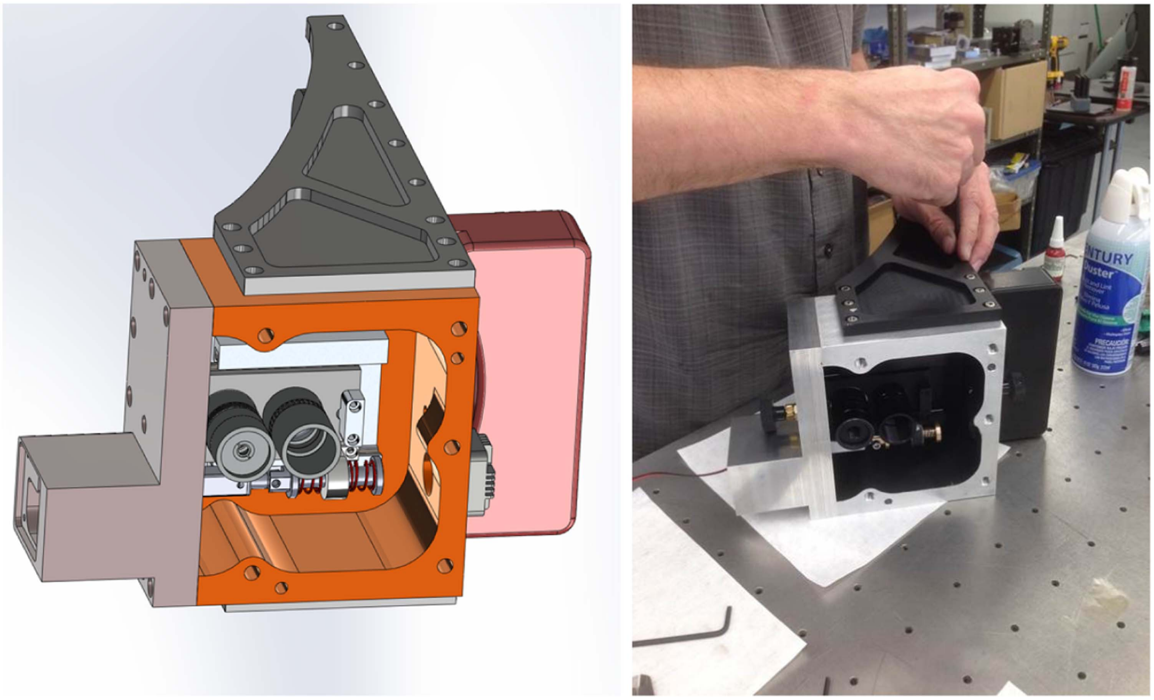

Figure 1. On the left is a prespective shot from the 3D CAD file for the camera upgrade highlighting here the slide for multiple magnifications. On the right is the final assembly before re-installation on the 26″.

Table 1
ICCD Measurements of Double Stars

WDS Desig. α,δ (2000)	Discoverer Designation			Epoch 2000.+	θ (°)	ρ (″)	n	Note
00004+5044	HJ	1923		15.777	278.9	11.51	2	
00004+0830	BU	732	AB	15.922	151.8	5.96	1	
00013+5604	HJ	1925		15.786	342.3	19.12	1	
00020+4530	J	864	AB	15.766	53.7	4.46	1	
00026+6606	STF	3053	AB	15.876	70.5	15.19	2	

Note.
A: this is the vector addition of measures of other pairs. B: this would have been published in an earlier paper in this series, but given the large change in position this measure was not published until its confirmation. C: confirming observation. D: unresolved. See Table 3.

(This table is available in its entirety in machine-readable form.)

2. At present, with the use of finder charts, the target is identified in the image from the finder CCD and then moved by the observer with the hand paddle, often taking additional finder images en route. Eventually, the first finder image will be compared against the UCAC4 catalog (Zacharias et al. 2013); offsets will be calculated and the object will automatically be moved to the appropriate place on the CCD. This improvement will substantially improve the objects per hour metric.
3. Other small improvements include the following.
   (a) Overshooting the slew slightly in R.A. so that after clamping the motion is against tracking. This will decrease the delay before finder images can be taken.
   (b) Test images from the finder camera displayed with ds_9[9] seem to indicate field identification can be done with shorter exposures than at present, again improving efficiency.
   (c) Keeping track of slow-motion rotations for the limited motion Decl. tangent arm and compensating for that in the Decl. slew will prevent the tangent arm re-centering delay.
   (d) Light baffles in the telescope tube may decrease the amount of stray light, improving the magnitude limit.
   (e) Implementing the suite of atmospheric monitoring tools: seeing monitor,[10] all sky camera,[11] and weather station to more correctly select objects to observe appropriate to the conditions.
   (f) Audio from the dome will allow the observer to hear clamps, relays, and the sound of motors to ensure safe operation. This could be part of the spycam described above or a separate system.
4. Due to the aperture of the telescope, atmospheric dispersion is significantly less than the resolution limit and inconsequential, as long as pointing is within a few

[9] Smithsonian Astrophysical Observatory.

[10] SBIG ST-402ME.

[11] SBIG AllSky340.

Table 2
Measurements of Systems with Orbits or Linear Solutions

WDS Desig. α,δ (2000)	Discoverer Designation			Epoch 2000.+	θ (°)	ρ (″)	n	O−C (°)	O−C (″)	References
00057+4549	STT	547	AB	15.766	189.3	6.03	1	0.4	0.12	Popovic & Pavlovic (1996)
								0.9	0.03	Kiyaeva et al. (2001)
00118+5140	HJ	1005		15.777	282.0	13.87	2	−0.7	−0.12	Hartkopf & Mason (2011)
00272+4959	STF	30	AB	15.805	315.2	13.27	1	0.5	−0.07	Hartkopf & Mason (2011)
00360+2959	STF	42	AB	15.775	20.3	6.25	2	−0.1	−0.06	Kiselev et al. (2009)
00384+4059	STF	44		15.775	274.0	12.80	2	0.1	0.06	Hartkopf & Mason (2011)
00464+3057	STFA	1	AB	15.777	46.3	47.33	2	0.1	0.01	Hartkopf & Mason (2011)
00474+5106	H 5	82	AB	15.805	74.7	56.37	1	−0.1	−0.16	Hartkopf & Mason (2011)
00550+2406	ENG	3		15.854	207.1	37.50	1	−0.0	−0.03	Hurowitz et al. (2013)
00591+5824	STI	1501		15.786	348.6	7.43	1	−0.7	−0.06	Hurowitz et al. (2013)
00594+0047	STF	80	AB	15.933	338.3	29.65	1	−0.2	0.07	Hartkopf & Mason (2011)
01048−0528	STF	86	AB	15.933	137.1	16.76	2	−0.1	0.00	Hartkopf & Mason (2011)
01182+5742	STI	1556		15.895	2.8	10.43	2	0.1	−0.03	Hurowitz et al. (2013)
01200+5747	STI	1571		15.895	353.4	12.00	2	−0.1	0.05	Hurowitz et al. (2013)
01207+4620	STF	112	AB	15.775	336.7	18.99	2	0.2	0.02	Hartkopf & Mason (2011)
01211+6439	S	397		15.876	341.4	57.33	1	0.0	0.07	Hartkopf & Mason (2011)
01402+7303	HJ	2055	AB	15.936	312.5	23.05	2	1.1	−0.20	Hurowitz et al. (2013)
01488−0125	STF	171	AB	15.043	164.4	34.34	2	−0.2	0.09	Hartkopf & Mason (2011)
02188+5714	BKO	168	AC	15.876	241.5	4.26	1	0.3	0.10	Hurowitz et al. (2013)
03187−1834	HJ	3565		15.076	121.8	8.01	1	0.1	−0.03	Hartkopf & Mason (2011)
03378+4943	WFC	250		15.966	67.6	11.11	1	0.9	−0.11	Hartkopf & Mason (2011)
03440+3822	STF	434	AB	15.966	82.5	33.56	1	0.3	−0.22	Hartkopf & Mason (2011)
03480+6840	WNO	16	BD	15.652	328.9	15.92	2	0.2	0.10	Hartkopf & Mason (2015)
03502+3449	ES	277	AB	15.035	141.1	21.02	1	0.2	0.34	Hartkopf & Mason (2015)
04013+6158	SLE	46		15.898	96.2	18.82	1	0.4	−0.22	Hartkopf & Mason (2011)
04544−0920	HJ	2242		15.800	19.1	21.43	2	−0.8	−0.08	Hartkopf & Mason (2011)
05225+4621	ES	1231	AC	15.966	19.4	18.69	1	0.7	0.24	Hurowitz et al. (2013)
06376+1211	S	529	AB	15.099	130.6	53.01	10	0.1	−0.11	Hartkopf & Mason (2011)
07057+5245	STF	1009	AB	15.224	147.8	4.40	1	−0.0	0.05	Hartkopf & Mason (2011)
07346+3153	STF	1110	AB	15.227	54.4	4.96	1	1.0	−0.10	Docobo et al. (2014)
09013+1516	STF	1300	AB	15.303	178.7	4.98	1	−0.3	−0.06	Zirm (2008)
10296+5611	HJ	1178		15.238	123.4	4.89	1	−0.3	0.14	Hartkopf & Mason (2011)
11246+5651	STI	2270		15.249	203.6	12.94	1	0.1	0.03	Hurowitz et al. (2014a)
11268+0301	STF	1540	AB	15.323	149.5	28.11	1	2.7	−0.51	Hopmann (1960)
11387+4507	STF	1561	AB	15.257	246.3	8.96	2	0.1	0.07	Hale (1994)
12227+3705	KZA	28	AB	15.323	216.8	33.56	1	−0.4	0.14	Hartkopf & Mason (2011)
12593+4245	HJ	1223	AB	15.323	189.3	18.34	1	−0.2	−0.04	Hartkopf & Mason (2011)
14024+4620	SWI	1		15.323	25.0:	3.76:	1	−1.0	0.14	Seymour et al. (2002)
14135+5147	STF	1821	AB	15.323	235.4	13.64	1	0.3	−0.15	Kiyaeva (2006)
								1.1	−0.59	Kiyaeva (2006)
14514+1906	STF	1888	AB	15.364	302.5	5.78	1	−0.1	0.17	Söderhjelm (1999)
15227−0132	STF	3093		15.558	155.3	22.52	1	−0.3	0.11	Hartkopf & Mason (2011)
15348+1032	STF	1954	AB	15.443	172.3	4.08	1	0.2	0.10	Mason et al. (2004)
15413+0350	BAL	2870		15.537	43.6	9.39	1	−0.4	−0.37	Hurowitz et al. (2014a)
15598+1723	STF	1993	AB	15.474	42.9	20.36	2	0.0	0.12	Hartkopf & Mason (2011)
16060+1319	STF	2007	AB	15.486	321.6	38.34	3	−0.3	−0.00	Hartkopf & Mason (2011)
16081+1703	STF	2010	AB	15.474	12.9	26.93	2	−0.6	−0.13	Hartkopf & Mason (2011)
16465+4759	ES	1089	AB	15.400	150.0	11.82	2	−0.3	0.01	Hurowitz et al. (2014a)
17146+1423	STF	2140	AB	15.526	103.1	5.25	1	0.2	0.61	Baize (1978)
17457+3452	AG	213		15.558	175.5	22.47	1	0.1	0.05	Hartkopf & Mason (2011)
19423+1937	HJ	2891		15.668	109.2	12.46	1	−0.6	−0.08	Hurowitz et al. (2014b)
20302+0321	DOO	87		15.616	33.3	11.87	1	0.4	0.18	Hartkopf & Mason (2011)
20425+4916	ARG	39	AB	15.657	182.8	15.05	2	−0.1	0.02	Hartkopf & Mason (2011)
20462+1554	STF	2725	AB	15.613	10.8	6.12	1	−0.8	−0.02	Mason & Hartkopf (2014)
20467+1607	STF	2727	AB	15.613	265.3	9.07	1	0.2	0.11	Hale (1994)
20520+4346	STT	416	AB	15.657	117.7	9.55	1	−0.0	0.08	Hartkopf & Mason (2011)
21072−1355	STF	2752	AB	15.766	179.9	4.39	1	−4.2	0.85	Hartkopf & Harshaw (2013)
21385+2323	POU	5445		15.703	191.1	25.94	2	−0.1	0.06	Hartkopf & Mason (2011)
21418+0145	HJ	3049		15.687	27.0	35.57	2	−0.3	−0.18	Hurowitz et al. (2014b)
21431+1338	HJ	1682		15.703	77.4	21.38	2	−0.1	−0.05	Hurowitz et al. (2014b)
21576+0501	HJ	3073		15.706	17.6	25.60	1	−2.8	−0.84	Hartkopf & Mason (2011)
22143+1711	STF	2877	AB	15.850	23.7	23.66	2	0.1	0.19	Hartkopf & Mason (2011)
22238+1044	HJ	3109		15.712	287.7	32.75	2	0.3	−0.11	Hartkopf & Mason (2011)

Table 2
(Continued)

WDS Desig. α,δ (2000)	Discoverer Designation			Epoch 2000.+	θ (°)	ρ (″)	n	O−C (°)	O−C (″)	References
22490+6834	STF	2947	AB	15.875	55.2	4.69	1	0.0	0.01	Hartkopf & Mason (2011)
23067+4111	HDS	3292		15.766	263.4	14.34	1	−0.3	−0.08	Hartkopf & Mason (2011)
23077+0636	STF	2976	AC	15.703	208.6	21.33	2	0.3	0.15	Hartkopf & Mason (2011)
23174+3813	HDS	3319	AB	15.712	253.0	18.14	2	0.1	−0.15	Hartkopf & Mason (2016)
23266+4520	GIC	192	AB	15.766	325.3	56.43	1	−0.5	0.00	Hurowitz et al. (2014b)
23412+7409	HJ	1905	AB	15.652	146.3	19.59	1	0.3	−0.05	Hurowitz et al. (2014b)
23536+5131	STTA	251	AB	15.714	208.1	47.99	1	0.3	0.11	Hartkopf & Mason (2011)

Table 3
Double Stars Not Found

Coordinate α,δ (2000)	Discoverer Designation			Most Recent Published Observation			Published Magnitude		Notes
				Date	Position Angle θ (°)	Separation ρ (″)	Primary	Secondary	
19068+6450	ES	1915		1921	146	3.5	11.4	11.9	1
19210+3931	MLB	861		1933	114	5.6	9.5	10.0	
20588+3530	SEI	1342		1896	100	4.1	8.7	10.0	2
20563+2709	J	2331	AC	1942	245	7.0	11.0	11.1	3

Note.
(1) Despite two published measures (Espin 1922, Stein 1926) there is no evidence of this pair in the field. Although separated in time by 18 years, the measures are quite similar, suggesting that the lack of current resolution is not due to differential proper motion. (2) Possibly a plate flaw was originally measured. Also not seen in Cava & Pascal (2004). (3) AB was also not seen, but Jonckheere (1943) estimated its magnitude as 14, which makes the nondetection insignificant.

hours of the zenith. However, correction for atmospheric dispersion (e.g., Risley prisms) will make observing much further off the zenith possible and also make the speckle camera design suitable for larger telescopes as a visitor instrument. There is sufficient space in the camera to add this capability, and plans to do so.

5. The current ICCD used by USNO, while very efficient, is quite venerable and due to the nonlinearity of intensifiers inappropriate for triple correlation, bi-spectrum or other reduction methodologies that retain the differential magnitude metric. Switching to an EMCCD, if it has sufficient speed and intensification, will allow us to also determine the Δm for systems. However, due to the nature of the focus and the limited transmissive properties of refractors, this will probably be limited to narrow wavelengths near visual such as Strömgren y or Johnson V.

3. RESULTS

3.1. Measures of Known Pairs

Table 1 presents the mean relative position of systems having no published orbital or rectilinear elements. The first two columns identify the system by providing its epoch-2000 coordinates and discovery designation. Columns three through five give the epoch of observation (expressed as a fractional Julian year), the position angle (in degrees), and the separation (in seconds of arc). Note that the position angle, measured from north through east, 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 factors: close separation, large magnitude difference, one or both components very faint, a large zenith distance, and poor seeing or transparency. The sixth column indicates the number of independent measurements (i.e., observations obtained on different nights) contained in the mean, and the seventh column flags any notes. The 1535 measurements in Table 1 have a mean separation of 16.″95, and a median separation of 11.″82. All pairs listed in Tables 1 and 2 are contained in the WDS (Mason et al. 2001), which summarizes measurements as well as containing cross-references and magnitudes and the precise position to aid in finding.

3.2. Orbit and Linear Calculations

Table 2 presents the mean relative positions for systems with published orbital determinations or linear solutions. The first six columns are identical to the corresponding columns of Table 1. Columns seven and eight give O–C residuals (in θ and ρ) to the determination referenced in column 9. The reference is either to a published orbit or linear calculation. Here, mean and median separations of 19.″56 and 15.″92 are determined. In two cases, it is not yet possible to ascertain which of the two solutions is preferable, so additional residual lines are provided.

3.3. Double Stars Not Found

Table 3 presents four systems that were observed but not detected. Possible reasons for nondetection include orbital or differential proper motion making the binary too close or too wide to resolve at the epoch of observation, a larger than expected Δm, incorrect pointing of the telescope, and misprints and/or errors in the original reporting paper. It is hoped that reporting these will encourage other double star astronomers to either provide corrections to the USNO observations or to verify the lack of detection.

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