# DATA MINING FOR DOUBLE STARS IN ASTROMETRIC CATALOGS

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## ABSTRACT

The US Naval Observatory has mined over 140 astrometric catalogs, including the Astrographic Catalogue and the Two Micron All Sky Survey, for measures of double stars. This resulted in 114,218 new measures of 47,007 different systems spanning 110 years; these are now included in the Washington Double Star catalog (WDS). This is the single largest data set ever added to the WDS. The measures are typically of wider pairs, most between $4''$ and $30''$; thus, their value in aiding orbit determination is limited. However, they have proven invaluable in the verification of systems and the determination of rectilinear motions of systems.

*Key word:* binaries: visual

*Online material:* machine-readable tables

## 1. INTRODUCTION

Since the 1960s, the United States Naval Observatory (USNO) has been heavily involved in converting astrometric-quality star catalogs to machine-readable form, primarily for use in determining high-precision proper motions, since this requires utilization of many sources over as long a time base as possible. This data set is called the Washington Fundamental Catalog (WFC), although no catalog was ever released under that name. The WFC contains data from 144 ground-based catalogs, most observed with transit circles or astrographs, totaling over 8 million star positions, some dating as early as the late 1800s. A list of WFC source catalogs is given in Table 5 of the *Guide to the Tycho-2 Catalogue*.[1] All WFC data were reduced to the International Celestial Reference System using the *Hipparcos* catalog (Perryman et al. 1997). Two notable results of the WFC were the generation of proper motions for Tycho-2 (Høg et al. 2000a, 2000b) and the Second US Naval Observatory CCD Astrograph Catalog (UCAC2; Zacharias et al. 2000). It was realized that in addition to being a source of information for proper motions, the WFC contains a wealth of double star measures that could go into the Washington Double Star catalog (WDS; Mason et al. 2001).[2]

During the course of extracting double star measures from the WFC, the final release of the Two Micron All Sky Survey (2MASS; Cutri et al. 2003) was made. It was realized that this data set also contains a wealth of double star information; therefore, using the same pair identification methodology, measures from the 2MASS Point Source Catalog[3] were extracted and added to the WDS.

This paper details the extraction process and provides tabular data for the individual measures, as well as giving important statistics. Section 2 explains the method used to match the input data to the WDS. Section 3 discusses the errors of the measures. Section 4 discusses newly identified double systems in the WFC, while § 5 describes the contributions of this new set of data to double star science.

## 2. EXTRACTION OF DATA

The WFC data set, having been designed to be used in proper motions work, was first precessed to J2000.0. Double star observations, on the other hand, are published at the equator and equinox for the epoch of observation. Therefore, the first step in the matching/extraction processes was to precess the WFC positions back to their original observation dates. The WFC epoch was computed as the mean of the right ascension and declination epochs for each star.[4] Since the measures are relative position angles and separation (not position on the sky), the adjustment due to precession is small for most of the systems; however, it can grow considerably for the older catalogs and for systems near the poles. An example is illustrated in Figure 1.

Following the precession of the data to the epoch of observation, a positional match was performed between the catalog positions in the WFC and the WDS. This match used a search radius of $120''$ from each WDS entry. Subsequently, the position angle and separation parameters of any two WFC stars within this radius were compared with the same parameters in the WDS. As this filter is for a correct match, if the position angle difference was less than $30°$ and the separation change was less than 30%, then the WFC system was selected as a match.

The actual extraction of data was done in three phases. The first extraction, done in late 2001, resulted in 36,547 measures. As double star positions were improved or additional doubles were found either in historical literature or by other observing programs, it was possible to do another match; this was done in late 2003, resulting in an additional 18,755 measures. Finally, following release of the 2MASS catalog, a similar matching procedure was used to identify double star measures in that catalog. The density of the 2MASS catalog posed a challenge, as there could be many pairs within a given large search window matching the general relative astrometry of the pair. Determining precise coordinates in earlier iterations of the project allowed the shrinking of these windows and, thus, the number of false positives. Matching with 2MASS and rematching with the other catalogs resulted in 58,916 more measures. This exercise is appropriate whenever large astrometric catalogs are added and will

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[1] Tycho-2 CD-ROM and http://www.astro.ku.dk/~cf/CD/docs/guide.pdf.
[2] See http://ad.usno.navy.mil/wds/wds.html for the most current version.
[3] 2MASS Point Source Catalog, 2003 all-sky release (Cutri et al. 2003). See http://pegasus.phast.umass.edu.

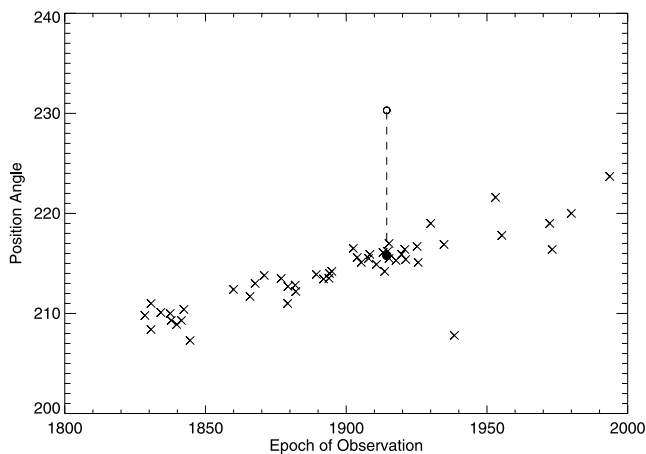[4] In some cases the mean epochs of the two coordinates differ slightly. See footnote 5.

F𝚒ɢ. 1.—Position angle vs. time for the measures of the double star STF 93 AB (WDS 02318+8916). Classical double star measures—all referred to their mean equator and equinox of observation—are represented with a cross. The calculated position angle from the Second Greenwich Catalog (Dyson 1935) precessed to J2000.0 is given as an open circle. Precessing the position back to equator and equinox of the observation (*filled circle*) changes the position angle significantly, where it matches contemporaneous measures quite well.

be repeated when the final UCAC release is matched and as warranted by the discovery of new wide binary systems.

Table 1 presents a listing of the astrographic and transit circle catalogs contributing double star measures. The catalog code is given in column (1), with the catalog name and reference given in columns (2) and (3). Catalogs coded with the lead "WFC" designation are photographic catalogs, whereas those with the lead "WFD" designation contain transit circle observations. Column (4) lists the number of contributing double star measures. It is worth noting that the vast majority of new measures are from two sources, the Astrographic Catalogue (AC; Urban et al. 1998) and the 2MASS Point Source Catalog.

A histogram of the epochs of observation is presented in Figure 2. As expected, this figure illustrates features in the AC and 2MASS. The AC was observed over several decades in the late 1800s and early 1900s and is the major source of pre-1930 data. The spike in the number of observations near the year 2000 is due primarily to the 2MASS catalog.

A histogram illustrating the separation coverage is given in Figure 3. The decrease in number at closer and wider separations is for two different reasons. At closer separations the inability to resolve closer companions is not unexpected given the limitations of short focus astrometry and the photographic process. In fact, in the compilation of the AC, measures of two "stars" that were closer than $2''$ were usually treated as a duplicate measure of a single star and combined. In addition, transit circle programs routinely avoided close doubles because they generally made poor reference stars. At wider separations the decrease is due to the lack of known binaries at these relative distances.

Table 2 presents all 114,218 measures. In this table, columns (1) and (2) identify the system by providing the epoch 2000 coordinate and discovery designation. Columns (3)–(5) give the mean values for epoch of observation[5] (expressed as fractional Besselian year), the position angle (in degrees), and the separation (in arcseconds). Column (6) indicates the number of ob-

servations contained in the means, while column (7) lists the appropriate source of the data from the list in Table 1. Column (8) lists the aperture of the telescope used in the observation, while the code in column (9) indicates the observing method. Column (10) is reserved for notes.

## 3. ERRORS OF MEASUREMENT

As an assessment of the quality of WFC measures, they have been compared to systems with calibration-quality orbits (Hartkopf et al. 2001). While these systems contain many definitive orbits, they also contain a like number of wider, long-period systems whose orbits, while describing the complete motion inexactly, provide perfectly reasonable ephemerides over the observation dates. Two examples of these are given in Figures 4 and 5. The full list of residuals to calibration systems is presented in Table 3. Columns (1)–(7) are the same as in Table 2 described above. Columns (8) and (9) give the $O − C$ (observed minus calculated) orbit residuals (in $\theta$ and $\rho$) to the orbit referenced in column (10).

Table 4 lists the mean orbit residuals for the different catalogs cited in Table 3. Column (1) lists the catalog code, while column (2) provides the number of measures from Table 2 included in the mean. Columns (3) and (4) give the mean $O − C$ orbit residual. Column (5) lists notes. Typically, these indicate when residuals have been determined from a subset of the wider ($\rho > 5''0$) data. Means of astrograph, transit circle, and all data are also provided. The systematic overestimating of very close systems that has been noted for other techniques (Worley 1981) is also seen here. When close systems are measured, at separations less than about $10''$ the error can be considerable, as shown in Figure 6. While these measures with larger errors are still of value in systems with few measures, their value in systems with many measures (especially those with contemporaneous double star observations) is of limited value. As is shown in Figure 7, the error has gone up slightly over the past century. However, comparison with Figure 6 indicates that these large-error systems are also those that are closest.

## 4. NEW WFC DOUBLES

The matching of the astrometric catalogs was done against the WDS in an effort to obtain more measures. However, in the match of known doubles additional pairs were flagged as possible new systems if they met one of two possible criteria: (1) the magnitude and separation fell within Aitken's (1932) proximity parameter; or (2) they were closer than $10''$. Modifications of Aitken's parameter for distinguishing between optical and physical pairs have been used (Rossiter 1955) in other surveys, and while it has significant limitations it is useful to highlight possible physical pairings of bright stars. The proximity limit was used because pairs closer than this may cause difficulties in the event of blended images. While many of these may be optical rather than physical, their proximity is the compelling factor, and these are pointedly "WFC doubles," not "WFC binaries." Identification of new pairs using these methods was not done with the 2MASS data (and will not be attempted with other deep catalogs, e.g., UCAC3) as the catalogs are so dense and deep the pairings identified by these techniques are more likely to be optical. While there are no doubt physical pairs contained within these catalogs, more traditional methods of identifying binaries (rather than doubles) such as Keplerian motion or common proper motion need to be used (see, e.g., Greaves 2004).

A total of 280 systems not previously resolved had more than one WFC measure in an initial inspection and were added to the

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[5] For transit circle catalogs these epochs are usually different, and the precision of the mean epoch presented in the table is dependent on the standard deviation of the individual epochs. For example, if the standard deviation is less than 0.1 yr, then the mean epoch is expressed in units of 0.01 yr.

TABLE 1
NUMBER OF DOUBLE STAR MEASURES

| Catalog Code (1) | Catalog Description (2) | Catalog Reference (3) | Number of Measures (4) |
|---|---|---|---|
| | | WFC | |
| WFC1939............. | Yale Observatory (−10 to −14) | Schlesinger & Barney (1939) | 76 |
| WFC1940a........... | Yale Observatory (−14 to −18) | Schlesinger & Barney (1940) | 62 |
| WFC1940b........... | Yale Observatory (−18 to −20) | Schlesinger & Barney (1940) | 29 |
| WFC1943a........... | Yale Observatory (−20 to −22) | Schlesinger & Barney (1943) | 10 |
| WFC1943b........... | Yale Observatory (−27 to −30) | Schlesinger & Barney (1943) | 51 |
| WFC1943c........... | Yale Observatory (−22 to −27) | Schlesinger & Barney (1943) | 62 |
| WFC1945a........... | Yale Observatory (−06 to −10) | Barney (1945) | 57 |
| WFC1945b........... | Yale Observatory (−02 to −06) | Barney (1945) | 45 |
| WFC1947............. | Yale Observatory (+15 to +20) | Barney (1947) | 94 |
| WFC1948............. | Yale Observatory (+09 to +15) | Barney (1948) | 125 |
| WFC1949............. | Yale Observatory (+01 to +05) | Barney (1949) | 107 |
| WFC1950a........... | Paris Observatory (+17 to +25) | Baillaud (1950) | 12 |
| WFC1950b........... | Yale Observatory (+01 to −02) | Barney (1950) | 33 |
| WFC1950c........... | Yale Observatory (+05 to +09) | Barney (1950) | 95 |
| WFC1954a........... | Cape Photographic Catalog (−30 to −35) | Jackson & Stoy (1954a) | 51 |
| WFC1954b........... | Cape Photographic Catalog (−35 to −40) | Jackson & Stoy (1954b) | 84 |
| WFC1954c........... | Cape Photographic Catalog (−52 to −56) | Jackson & Stoy (1955) | 79 |
| WFC1954d........... | Yale Observatory (+20 to +30) | Barney (1953, 1954) | 177 |
| WFC1954e........... | Yale Observatory (+85 to +90) | Barney & van Woerkom (1954) | 5 |
| WFC1958a........... | AGK2 North of −2°.5 (Bergedorf) | Schorr & Kohlschuetter (1958) | 1666 |
| WFC1958b........... | AGK2 North of −2°.5 (Bonn) | Schorr & Kohlschuetter (1958) | 1057 |
| WFC1958c........... | Cape Photographic Catalog (−56 to −60) | Jackson & Stoy (1958) | 51 |
| WFC1958d........... | Cape Photographic Catalog (−60 to −64) | Jackson & Stoy (1958) | 76 |
| WFC1959............. | Yale Observatory (+50 to +60) | Barney et al. (1959) | 242 |
| WFC1966a........... | Cape Photographic Catalog (−64 to −68) | Stoy (1966) | 71 |
| WFC1966b........... | Cape Photographic Catalog (−68 to −72) | Stoy (1966) | 53 |
| WFC1966c........... | Cape Photographic Catalog (−72 to −76) | Stoy (1966) | 32 |
| WFC1966d........... | Cape Photographic Catalog (−76 to −80) | Stoy (1966) | 30 |
| WFC1967............. | Yale Observatory (−30 to −35) | Hoffleit (1967) | 85 |
| WFC1968a........... | Cape Photographic Catalog (−80 to −89) | Stoy (1968a) | 24 |
| WFC1968b........... | Yale Observatory (−35 to −40) | Hoffleit (1968) | 93 |
| WFC1970............. | Yale Observatory (−40 to −50) | Hoffleit (1970) | 152 |
| WFC1971............. | Yale Observatory (−70 to −90) | Lu (1971) | 210 |
| WFC1975............. | AGK3 North of −2°.5 | Heckmann & Dieckvoss (1975) | 2805 |
| WFC1983a........... | Sydney Observatory (−48 to −54) | Eichhorn et al. (1983) | 173 |
| WFC1983b........... | Sydney Observatory (−51 to −63.5) | King & Lomb (1983) | 129 |
| WFC1983c........... | Yale Observatory (−60 to −70) | Fallon & Hoffleit (1983) | 121 |
| WFC1992............. | CPC2 | Zacharias et al. (1992) | 1163 |
| WFC1994............. | FOKAT | Bystrov et al. (1994) | 576 |
| WFC1998............. | Astrographic Catalog 2000 | Urban et al. (1998) | 54242 |
| WFC1999............. | Twin Astrographic Catalog | Zacharias & Zacharias (1999) | 2668 |
| Total WFC ....... | ... | ... | 66973 |
| | | WFD | |
| WFD1889............. | Second Melbourne Catalog | Ellery & White (1889) | 7 |
| WFD1904............. | Kat. der Astron. Gesell. | de Ball (1904) | 76 |
| WFD1906a........... | Cape General Catalog | Gill (1906) | 11 |
| WFD1906b........... | Kat. der Astron. Gesell. | Becker (1906) | 47 |
| WFD1907............. | Lick Observatory | Tucker (1907) | 15 |
| WFD1908a........... | Bonn University | Küstner (1908) | 1 |
| WFD1908b........... | Kat. der Astron. Gesell. | Skinner (1908) | 73 |
| WFD1909............. | Greenwich Second Nine Year Catalog | Christie (1909) | 127 |
| WFD1914............. | Abbadia Observatory (Algiers zone) | Abbadia Obs. (1914) | 123 |
| WFD1915a........... | Abbadia Observatory (Paris zone) | Abbadia Obs. (1915) | 206 |
| WFD1915b........... | Cape Fundamental Catalog | Gill & Hough (1915) | 1 |
| WFD1916............. | Berlin-Babelsberg (+79 to +90) | Freundlich (1916) | 13 |
| WFD1917a........... | Abbadia Observatory (San Fernando zone) | Abbadia Obs. (1917) | 9 |
| WFD1917b........... | Third Melbourne Catalog | Ellery & Baracchi (1917) | 21 |
| WFD1918a........... | Albany Catalog | Boss (1910) | 162 |
| WFD1918b........... | Albany Catalog | Boss & Roy (1918) | 31 |
| WFD1919............. | La Plata A Catalog | Delavan (1919) | 36 |
| WFD1920a........... | Second Cape Fundamental Catalog | Hough (1920) | 3 |

TABLE 1—*Continued*

| Catalog Code (1) | Catalog Description (2) | Catalog Reference (3) | Number of Measures (4) |
|---|---|---|---|
| | | WFD | |
| WFD1920b........... | Greenwich Catalog | Dyson (1920) | 166 |
| WFD1920c........... | USNO | Eichelberger (1920) | 43 |
| WFD1921............. | Bonn University | Küstner & Monnichmeyer (1921) | 14 |
| WFD1923............. | Berlin-Babelsberg (+31 to +40) | Prager (1923) | 10 |
| WFD1924a........... | Alger Observatory | Rambaud (1924) | 44 |
| WFD1924b........... | La Plata C Catalog | Martinez (1924) | 14 |
| WFD1925............. | Lick Observatory | Tucker (1925) | 2 |
| WFD1926a........... | Konigsberg Observatory | Przybyllok (1926) | 5 |
| WFD1926b........... | Lund Observatory | Gyllenberg (1926) | 111 |
| WFD1927a........... | Bonn University | Küstner (1927) | 1 |
| WFD1927b........... | Munich | Oertel (1927) | 75 |
| WFD1927c........... | Munich | Oertel (1927) | 86 |
| WFD1928a........... | First Bergedorf | Dolberg (1928) | 120 |
| WFD1928b........... | First Cape Catalog | Jones (1928) | 33 |
| WFD1928c........... | Leiden Observatory | Hins (1928) | 1 |
| WFD1928d........... | San Luis Catalog | Boss & Boss (1928) | 357 |
| WFD1929a........... | La Plata B Catalog | Aguilar & Dawson (1929) | 19 |
| WFD1929b........... | Nice Observatory | Fayet (1929) | 11 |
| WFD1929c........... | Paris Observatory | Chatelu (1929) | 130 |
| WFD1931............. | Albany Catalog | Boss (1931) | 1056 |
| WFD1933a........... | Pulkovo Observatory | Morin (1933) | 3 |
| WFD1933b........... | USNO | Morgan (1933) | 32 |
| WFD1934a........... | Leiden Observatory | Hins (1934) | 2 |
| WFD1935............. | Second Greenwich Catalog | Dyson (1935) | 102 |
| WFD1936............. | La Plata D Catalog | Manganiello (1936) | 23 |
| WFD1937............. | Toulouse Observatory | Paloque (1937) | 4 |
| WFD1938............. | La Plata F Catalog | Martinez (1938) | 46 |
| WFD1939............. | Madison Catalog | Flint & Roy (1939) | 6 |
| WFD1940............. | Pulkovo Observatory | Seraphimoff (1940) | 6 |
| WFD1941............. | Toulouse Observatory | Paloque (1941) | 102 |
| WFD1943............. | La Plata Observatory | Martinez (1943) | 16 |
| WFD1947............. | La Plata E Catalog | Tapia (1947) | 2 |
| WFD1948............. | USNO | Morgan & Scott (1948) | 31 |
| WFD1949a........... | Second Cape Catalog | Jackson (1949) | 97 |
| WFD1949b........... | USNO | Watts & Adams (1949) | 22 |
| WFD1951a........... | Third Cape Catalog | Jackson (1951) | 51 |
| WFD1951b........... | Lund Observatory | Reiz (1951) | 9 |
| WFD1952............. | USNO | Watts et al. (1952) | 9 |
| WFD1953............. | First Cape Catalog | Jackson (1953) | 120 |
| WFD1954a........... | Cape Photographic Standard ($-35$ to $-40$) | Jackson & Stoy (1954b) | 2 |
| WFD1954b........... | Cordoba D Catalog | Guerin & Bobone (1954) | 87 |
| WFD1958a........... | Cape Photographic Standard ($-56$ to $-64$) | Jackson & Stoy (1958) | 3 |
| WFD1958b........... | Cape Photographic Standard ($-56$ to $-64$) | Jackson & Stoy (1958) | 3 |
| WFD1959............. | La Plata Observatory | Martinez (1959) | 156 |
| WFD1963............. | System of Fundamental Proper Motions | Scott (1963) | 6 |
| WFD1964............. | USNO | Adams & Bestul (1964) | 24 |
| WFD1966a........... | Cape Photographic Standard ($-64$ to $-68$) | Stoy (1966) | 1 |
| WFD1966b........... | Cape Photographic Standard ($-68$ to $-80$) | Stoy (1966) | 1 |
| WFD1968a........... | Second Cape Catalog | Stoy (1968b) | 88 |
| WFD1968b........... | Cape Photographic Standard ($-80$ to $-90$) | Stoy (1968a) | 1 |
| WFD1969............. | First Greenwich Catalog | Woolley (1969) | 94 |
| WFD1973............. | Cordoba E Catalog | Bobone (1973) | 5 |
| WFD1985............. | Carlsberg Meridian Catalog | CUO, RGO, ROA (1985)[a] | 567 |
| WFD1988............. | Perth Observatory | Harwood (1988) | 60 |
| WFD1989............. | Tokyo Photoelectric Meridian Catalog | Yoshizawa & Suzuki (1989) | 30 |
| WFD1990............. | SRS Catalog | Smith et al. (1990) | 3 |
| WFD1997............. | USNO | Holdenried & Rafferty (1997) | 168 |
| WFD2000............. | USNO (pole-to-pole) | Rafferty & Holdenried (2000) | 65 |
| WFD9999............. | Heidelberg Zodiacal 50 | G. Wycoff 2005, unpublished | 8 |
| Total WFD ....... | ... | ... | 5321 |
| TMA2003............... | 2MASS Catalog | 2003 All-Sky Release | 41924 |
| All ................. | ... | ... | 114218 |

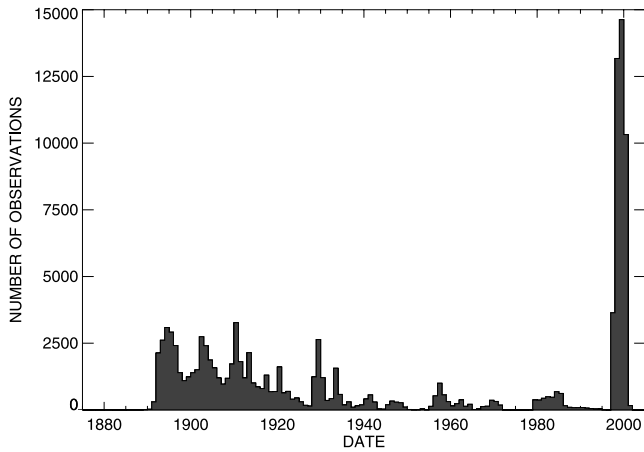[a] Copenhagen University Observatory, Royal Greenwich Observatory, and Instituto y Observatorio de Marina.

WDS. Systems with only one measure were not added, as the uncertainty in quality of the various techniques made their veracity subject to doubt. The current WDS entries for these systems are provided in Table 5. In this table, column (1) gives the abbreviated J2000.0 coordinates, which also serve as the WDS designation. Column (2) provides the discovery designation. The WFC designation given in this column is only approximately sequential in right ascension due to the timing of their confirmations. Columns (3) and (4) give the dates of first and last observation, while column (5) gives the number of observations. The position angles of the binary on the first and last observation dates are given in columns (6) and (7). The separations in arcseconds for these observations are given in columns (8) and (9). Finally, columns (10) and (11) give the magnitude of the primary and secondary stars, respectively. Magnitudes given to a tenth of a magnitude are provided by the source catalog. For photographic catalogs (coded with prefix "WFC" in Table 1), these can be taken as approximately *B*. For visual catalogs (those coded with prefix "WFD" in Table 1), these can be taken as approximately *V*. When given to the nearest hundredth of a magnitude, the source of the magnitude is the $V_T$ magnitude of Tycho-2.

Stars with entries in the Tycho-2 catalog (Høg et al. 2000a, 2000b) have been inspected to make sure their proper motions are not incompatible. In no case was this found to be true. Again, the accuracy in the listing of magnitudes in Table 5 indicates which new WFC doubles have proper motions contained in Tycho-2.

In addition to these new systems with multiple epochs, there were a total of 153 "single epoch" WFC stars. While these represent measures of questionable detections, they are being retained until inspection either at USNO or at outside institutions. While the greatest hope for these systems is possibly the UCAC project (Zacharias et al. 2000), 69 systems have been confirmed by the Tycho Double Star reduction project (Fabricius
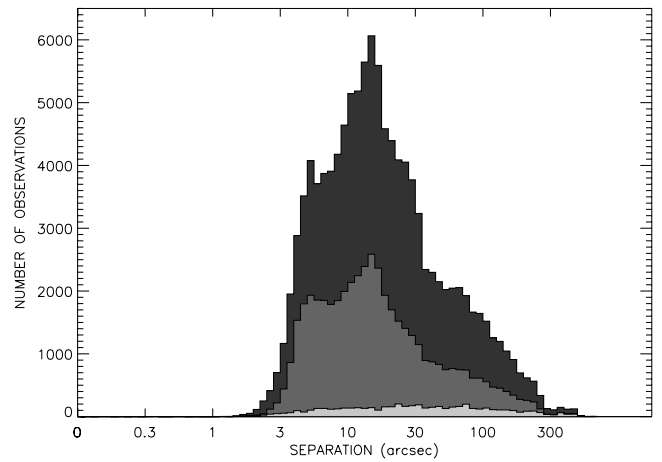
et al. 2002) and 14 by 2MASS. Six others were confirmed with the USNO speckle camera and 26 inch (0.7 m) refractor in the spring of 2001 (Mason et al. 2002), and one in 2002 (Mason et al. 2004). Additional single-epoch new doubles will be added to the WDS as they are confirmed.

## 5. CONTRIBUTIONS TO DOUBLE STARS

This compilation of data added to the WDS represents the single largest data set added; 16% of the mean positions in the WDS come from this work, and they represent 46% of the known systems. However, they are the wider, typically slow-moving systems. For most double stars it takes quite a few measures spanning several years to classify them as having motion that is either Keplerian or rectilinear. So, while the data set is large and helpful in cases of verification and linear proper motions, its value in the case of orbit systems is severely limited. A summary of the WFC contributions to double star measures is presented in Table 6. In any event, 109 systems, including those listed in Table 3, have orbital determinations. The greater contribution is expected to come for systems with linear solutions (i.e., differential proper motion), which is expected to be significant. A total of 1141 systems have these types of solutions (W. T. Hartkopf et al. 2006, in preparation).

TABLE 2

MEASUREMENTS OF DOUBLE STARS

| WDS or $\alpha$, $\delta$ (J2000.0) (1) | Discovery Designation (2) | Epoch (3) | $\theta$ (deg) (4) | $\rho$ (arcsec) (5) | $n$ (6) | Catalog Code (see Table 1) (7) | Aperture (inches) (8) | Method (9) | Notes (10) |
|---|---|---|---|---|---|---|---|---|---|
| 00000+3852 ............................... | BU 860 | 1999.75 | 107.8 | 6.34 | 1 | TMA2003 | 51 | F | K |
| 00000+4004 ............................... | ES 2543 | 1999.75 | 252.3 | 4.51 | 1 | TMA2003 | 51 | F | K |
| 00001+5400 ............................... | ES 704 | 1999.71 | 116.0 | 4.41 | 1 | TMA2003 | 51 | F | K |
| 00002−2519 ............................... | COO 273 | 1910.75 | 9.7 | 9.028 | 1 | WFC1998 | 13 | G | |
| 00002−2519 ............................... | COO 273 | 1910.84 | 11.8 | 8.484 | 1 | WFC1998 | 13 | G | |
| 00002−2519 ............................... | COO 273 | 1933.73 | 12.2 | 8.510 | 1 | WFC1943c | 05 | G | |
| 00002−2519 ............................... | COO 273 | 2000.71 | 10.4 | 8.50 | 1 | TMA2003 | 51 | F | K |
| 00003−0654 ............................... | LDS 6079 | 1998.77 | 1.3 | 158.39 | 1 | TMA2003 | 51 | F | K |
| 00003+1642 ............................... | HJ 318 | 1999.83 | 61.8 | 26.51 | 1 | TMA2003 | 51 | F | K |
| 00003+5651 ............................... | CTT 1 | 1906.89 | 90.1 | 49.423 | 1 | WFC1998 | 13 | G | |
| 00003+5651 ............................... | CTT 1 | 1908.83 | 91.6 | 49.549 | 1 | WFC1998 | 13 | G | |
| 00003+5651 ............................... | CTT 1 | 1917.93 | 91.4 | 48.608 | 1 | WFC1998 | 13 | G | |
| 00003+5651 ............................... | CTT 1 | 1999.71 | 92.8 | 46.74 | 1 | TMA2003 | 51 | F | K |
| 00004+0830 ............................... | BU 732 | 2000.72 | 151.7 | 5.86 | 1 | TMA2003 | 51 | F | K |
| 00004+0830 ............................... | BU 732 AC | 1897.80 | 143.0 | 152.220 | 1 | WFC1998 | 13 | G | |

NOTES.—( K): Infrared measure, i.e., 2MASS. Table 2 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.
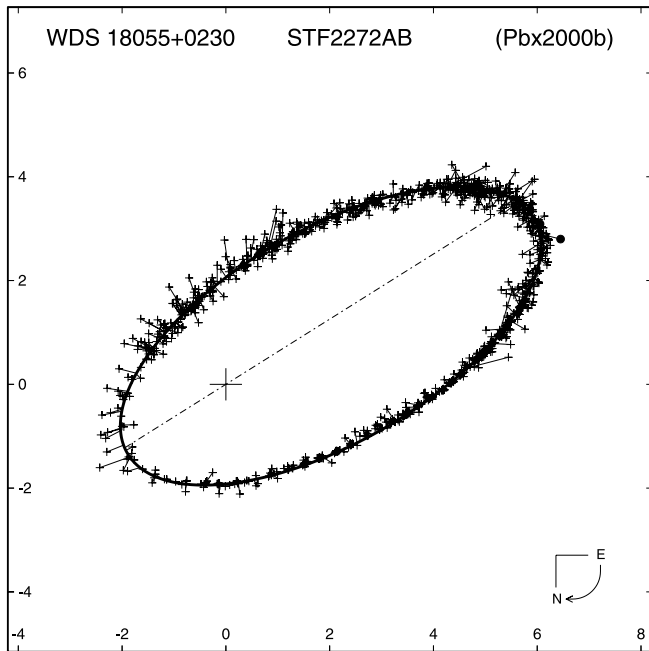


FIG. 4.—All double star measures of STF 2272 AB ( WDS 18055+0230) plotted against the definitive orbit of Pourbaix (2000). The two filled circles at the widest separation are the WFC measures. All other double star measures are shown by plus signs. $O - C$ lines connect data points with their predicted positions on the orbit. The broken line is the line of nodes, and the axes of the figure are in arcseconds. The direction of motion is indicated in the lower right corner. Position angles are measured from north through east.



FIG. 5.—All double star measures of STF 1321 AB ( WDS 09144+5241) plotted against the provisional ( but still calibration-quality) orbit of Chang (1972). In this case only the portion of the orbit (48° or 13% of a period) with data is plotted. As noted in Table 3, this system has the greatest number of WFC measures. All symbols are as in Fig. 4.

TABLE 3
WFC Measures of Calibration-Quality Orbits

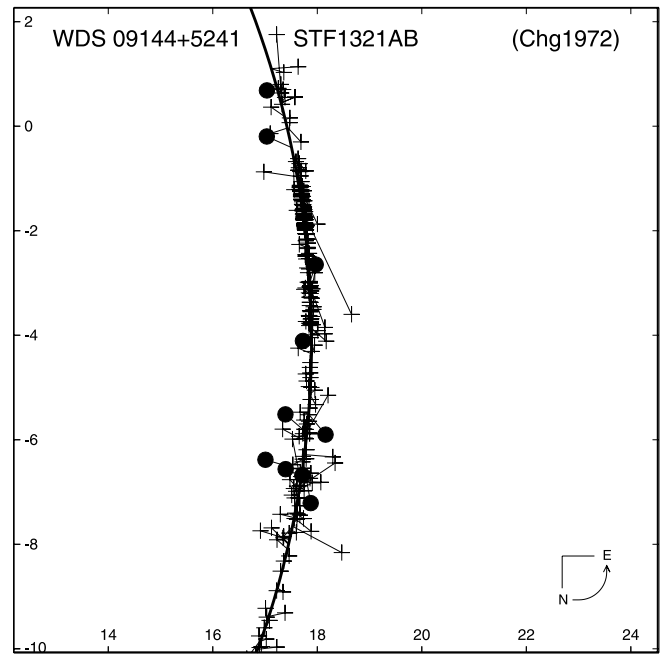| WDS or $\alpha$, $\delta$ (J2000.0) (1) | Discovery Designation (2) | BY (3) | $\theta$ (deg) (4) | $\rho$ (arcsec) (5) | $N$ (6) | Catalog Code (see Table 1) (7) | $O - C_\theta$ (deg) (8) | $O - C_\rho$ (arcsec) (9) | Orbit Reference (10) |
|---|---|---|---|---|---|---|---|---|---|
| 00057+4549 ................. | STT 547 | 1915.80 | 142.4 | 5.235 | 1 | WFD1931 | 2.1 | 0.38 | Popovic & Pavlovic (1996) |
| | | 1929.78 | 147.0 | 6.014 | 1 | WFC1958a | −1.9 | 0.86 | |
| | | 1956.92 | 155.3 | 4.360 | 1 | WFC1975 | −7.7 | −1.30 | |
| | | 1998.84 | 181.0 | 6.03 | 1 | TMA2003 | −0.6 | 0.05 | |
| 01398−5612 ................. | DUN 5 | 1910.20 | 218.4 | 7.912 | 4 | WFD1928d | 0.7 | −0.37 | van Albada (1957) |
| | | 1920.80 | 220.3 | 9.252 | 1 | WFC1998 | 7.1 | 0.38 | |
| | | 1938.01 | 208.2 | 8.948 | 8 | WFD1953 | 1.1 | −0.75 | |
| | | 1946.90 | 201.1 | 10.221 | 1 | WFC1958c | −3.2 | 0.15 | |
| | | 1999.82 | 189.9 | 11.15 | 1 | TMA2003 | −0.7 | −0.37 | |
| 02020+0246 ................. | STF 202 | 1913.60 | 303.2 | 2.824 | 1 | WFD1931 | −10.9 | 0.18 | Scardia (1983) |
| 02442+4914 ................. | STF 296 | 1999.80 | 304.8 | 20.52 | 1 | TMA2003 | 0.8 | 0.48 | Hopmann (1958) |
| 03368+0035 ................. | STF 422 | 1899.90 | 244.7 | 5.645 | 2 | WFD1918b | −3.4 | −0.73 | Hopmann (1964 |
| | | 1908.98 | 250.5 | 7.475 | 1 | WFC1998 | 0.4 | 1.07 | |
| 05364+2200 ................. | STF 742 | 1902.7 | 261.8 | 4.075 | 3 | WFD1915a | 1.4 | 0.41 | Hopmann (1973) |
| | | 1915.07 | 259.1 | 4.392 | 2 | WFD1928a | −3.1 | 0.67 | |
| | | 1934.8 | 258.0 | 3.594 | 3 | WFD1969 | −7.1 | −0.22 | |
| | | 1980.69 | 270.8 | 4.227 | 5 | WFD1997 | −0.4 | 0.21 | |
| | | 1997.85 | 273.0 | 3.59 | 1 | TMA2003 | −0.4 | −0.49 | |
| 07201+2159 ................. | STF 1066 | 1980.24 | 223.0 | 6.099 | 8 | WFD1997 | 1.6 | 0.01 | Hopmann (1960) |
| 08122+1739 ................. | STF 1196 AB-C | 1907.0 | 112.1 | 5.951 | 3 | WFD1929c | −4.7 | 0.45 | Heintz (1996) |
| 09144+5241 ................. | STF 1321 | 1915.10 | 69.1 | 18.931 | 1 | WFD1931 | 0.2 | −0.02 | Chang (1972) |
| | | 1917.7 | 69.2 | 18.166 | 4 | WFD1926a | −0.4 | −0.73 | |
| | | 1918.19 | 69.1 | 18.591 | 1 | WFD1925 | −0.6 | −0.30 | |
| | | 1919.46 | 67.8 | 19.274 | 2 | WFD1933b | 0.1 | 0.24 | |
| | | 1925.95 | 72.2 | 18.244 | 6 | WFD1935 | 0.5 | −0.50 | |
| | | 1930.03 | 71.8 | 19.093 | 1 | WFC1958a | −1.0 | 0.43 | |
| | | 1947.01 | 76.8 | 18.195 | 1 | WFC1959 | −0.6 | −0.14 | |
| | | 1958.11 | 81.5 | 18.164 | 1 | WFC1975 | 1.0 | 0.06 | |
| | | 1986.02 | 89.3 | 17.035 | 4 | WFD1985 | 0.6 | −0.48 | |
| | | 1998.93 | 92.3 | 17.05 | 1 | TMA2003 | −0.3 | −0.18 | |
| 11182+3132................. | STF 1523 | 1915.65 | 108.4 | 3.873 | 1 | WFD1931 | −4.9 | 0.79 | Mason et al. (1995) |
| 12160+0538 ................. | STF 1621 | 1914.9 | 139.1 | 2.511 | 1 | WFD1928a | −1.9 | 0.40 | Söderhjelm (1999) |
| 13550−0804 ................. | STF 1788 | 1980.04 | 96.0 | 3.503 | 8 | WFD1997 | 1.8 | 0.13 | Hopmann (1970) |
| | | 1999.16 | 97.7 | 2.75 | 1 | TMA2003 | 0.2 | −0.74 | |
| 14131+5520 ................. | STF 1820 | 1920.5 | 84.3 | 2.602 | 2 | WFD1928a | −0.6 | 0.38 | Kiyaeva et al. (1998) |
| 14575−2125 ................. | H28 | 1933.40 | 298.3 | 19.928 | 1 | WFC1943a | −0.4 | 0.15 | Hale (1994) |
| | | 1938.80 | 300.1 | 20.310 | 8 | WFD1953 | 0.7 | 0.10 | |
| | | 1939.4 | 307.4 | 25.952 | 4 | WFD1948 | 8.0 | 5.69 | |
| | | 1970.54 | 303.0 | 22.631 | 4 | WFC1992 | 0.0 | −0.03 | |
| | | 1985.1 | 306.4 | 23.359 | 3 | WFC1994 | 2.0 | −0.36 | |
| 16147+3352 ................. | STF 2032 | 1890.61 | 202.8 | 4.810 | 3 | WFD1917b | −4.7 | 0.79 | Scardia (1979) |
| | | 1910.3 | 214.5 | 5.317 | 1 | WFD1928d | −1.1 | 0.57 | |
| | | 1912.3 | 221.8 | 5.597 | 1 | WFD1931 | 5.6 | 0.78 | |
| | | 1993.3 | 236.7 | 7.704 | 8 | WFD2000 | 1.9 | 0.82 | |
| | | 1994.54 | 236.1 | 6.887 | 6 | WFD2000 | 1.1 | −0.02 | |
| | | 1998.26 | 236.2 | 6.25 | 1 | TMA2003 | 0.6 | −0.73 | |
| 17053+5428 ................. | STF 2130 | 1913.50 | 130.6 | 2.785 | 1 | WFD1931 | −1.5 | 0.46 | Heintz (1981) |
| 17153−2636 ................. | SHJ 243 | 1929.3 | 182.9 | 3.660 | 4 | WFD1949b | 5.4 | −0.59 | Irwin et al. (1996) |
| | | 1934.34 | 178.0 | 4.699 | 4 | WFD1951a | 3.0 | 0.43 | |
| | | 1938.88 | 172.1 | 4.910 | 8 | WFD1953 | −0.8 | 0.62 | |
| | | 1940.6 | 175.9 | 4.829 | 9 | WFD1948 | 3.9 | 0.54 | |
| | | 1980.44 | 158.2 | 5.312 | 8 | WFD1997 | 4.1 | 0.70 | |
| 18055+0230 ................. | STF 2272 | 1935.7 | 117.4 | 6.798 | 6 | WFD1969 | −1.1 | 0.06 | Pourbaix (2000) |
| | | 1939.14 | 113.8 | 7.031 | 8 | WFD1953 | −1.8 | 0.32 | |
| 18443+3940 ................. | STF 2383 Cc-D | 1905.00 | 128.2 | 2.504 | 15 | WFD1927b | 3.3 | 0.18 | Docobo & Costa (1984) |
| | | 1912.80 | 117.0 | 2.708 | 1 | WFD1931 | −4.5 | 0.40 | |
| | | 1980.8 | 87.2 | 3.308 | 7 | WFD1997 | −3.6 | 1.01 | |

TABLE 3—*Continued*

| WDS or $\alpha$, $\delta$ (J2000.0) (1) | Discovery Designation (2) | BY (3) | $\theta$ (deg) (4) | $\rho$ (arcsec) (5) | $N$ (6) | Catalog Code (see Table 1) (7) | $O - C_\theta$ (deg) (8) | $O - C_\rho$ (arcsec) (9) | Orbit Reference (10) |
|---|---|---|---|---|---|---|---|---|---|
| 19121+4951 .................... | STF 2486 | 1901.54 | 217.6 | 9.837 | 1 | WFC1998 | 0.0 | 0.50 | Hale (1994) |
| | | 1902.54 | 223.1 | 9.958 | 1 | WFC1998 | 5.6 | 0.64 | |
| | | 1909. | 205.7 | 11.383 | 2 | WFD1921 | −11.2 | 2.19 | |
| | | 1914.10 | 220.3 | 9.313 | 1 | WFD1931 | 3.9 | 0.21 | |
| | | 1920.2 | 217.5 | 9.139 | 2 | WFD1928a | 1.7 | 0.15 | |
| | | 1928.4 | 207.6 | 9.653 | 4 | WFD1935 | −7.4 | 0.82 | |
| | | 1929.65 | 216.3 | 8.576 | 1 | WFC1958a | 1.5 | −0.24 | |
| | | 1957.57 | 209.8 | 7.891 | 1 | WFC1975 | −2.1 | −0.40 | |
| | | 2000.32 | 206.2 | 7.40 | 1 | TMA2003 | −0.2 | −0.11 | |
| 20462+1554 .................... | STF 2725 | 1903.80 | 11.0 | 5.326 | 1 | WFC1998 | 8.7 | 0.20 | Hopmann (1973) |
| | | 1913.5 | 0.5 | 5.513 | 1 | WFD1931 | −2.8 | 0.28 | |
| | | 1914.58 | 6.6 | 5.133 | 2 | WFD1928a | 3.2 | −0.11 | |
| | | 1998.35 | 9.9 | 6.02 | 1 | TMA2003 | −0.7 | −0.04 | |
| 20467+1607 .................... | STF 2727 | 1913.5 | 270.9 | 11.525 | 1 | WFD1931 | 1.0 | 0.73 | Hale (1994) |
| | | 1934.20 | 270.6 | 10.266 | 7 | WFD1969 | 1.5 | −0.19 | |
| | | 1939.78 | 268.8 | 10.767 | 1 | WFC1947 | 0.0 | 0.41 | |
| | | 1940.67 | 267.6 | 10.756 | 8 | WFD1953 | −1.2 | 0.41 | |
| | | 1992. | 262.4 | 9.640 | 7 | WFD2000 | −3.9 | 0.22 | |
| 21069+3845 .................... | STF 2758 | 1928.86 | 134.8 | 24.450 | 1 | WFC1998 | 0.2 | −0.52 | Kisselev et al. (1997) |
| | | 1931.87 | 136.6 | 25.240 | 1 | WFC1998 | 1.2 | −0.02 | |
| | | 1957.56 | 140.9 | 27.453 | 1 | WFC1975 | −0.6 | −0.12 | |
| | | 1980.07 | 144.0 | 29.130 | 8 | WFD1997 | −2.2 | −0.24 | |
| | | 1998.47 | 149.6 | 30.63 | 1 | TMA2003 | −0.0 | −0.02 | |
| 21441+2845 .................... | STF 2822 | 1915.60 | 109.2 | 2.043 | 1 | WFD1931 | −22.7 | 0.37 | Heintz (1995) |
| 22038+6438 .................... | STF 2863 | 1901.1 | 282.4 | 7.015 | 5 | WFD1909 | 1.0 | 0.15 | Zeller (1965) |
| | | 1915.20 | 280.1 | 7.375 | 1 | WFD1931 | −0.2 | 0.30 | |
| | | 1994.80 | 275.5 | 7.960 | 4 | WFD2000 | 0.6 | −0.20 | |
| 22266−1645 .................... | SHJ 345 | 1895.30 | 307.1 | 8.158 | 2 | WFD1908b | −0.8 | 0.99 | Hale (1994) |
| | | 1904.64 | 313.2 | 7.418 | 4 | WFD1920c | 3.9 | 0.66 | |
| | | 1914.20 | 312.6 | 6.846 | 1 | WFD1931 | 1.8 | 0.51 | |
| | | 1928.65 | 312.6 | 5.617 | 6 | WFD1949a | −1.1 | −0.03 | |
| | | 1929.09 | 313.0 | 5.431 | 4 | WFD1949b | −0.8 | −0.20 | |
| | | 1939.39 | 317.5 | 5.623 | 8 | WFD1953 | 1.1 | 0.51 | |
| | | 1979.62 | 340.2 | 3.453 | 8 | WFD1997 | 4.7 | 0.57 | |
| 23595+3343 .................... | STF 3050 | 1915.70 | 221.2 | 2.106 | 1 | WFD1931 | −6.0 | 0.08 | Starikova (1977) |

| Catalog Code (see Table 1) (1) | N (2) | $O - C_\theta$ (deg) (3) | $O - C_\rho$ (arcsec) (4) | Notes (5) |
|---|---|---|---|---|
| WFC1943a...................... | 1 | −0.4 | 0.15 | |
| WFC1947........................ | 1 | −0.0 | 0.41 | |
| WFC1958a...................... | 3 | −0.5 ± 1.4 | 0.35 ± 0.45 | |
| WFC1958c....................... | 1 | −3.2 | 0.15 | |
| WFC1959........................ | 1 | −0.6 | −0.14 | |
| WFC1975........................ | 4 | −2.4 ± 3.3 | −0.44 ± 0.52 | 1 |
| WFC1992........................ | 1 | −0.0 | −0.03 | |
| WFC1994........................ | 1 | 2.0 | −0.36 | |
| WFC1998........................ | 7 | 3.3 ± 3.4 | 0.32 ± 0.47 | |
| All astrographs............ | 20 | 0.5 ± 3.5 | 0.09 ± 0.52 | 2 |
| WFD1908a...................... | 1 | −11.9 | 2.19 | |
| WFD1909........................ | 1 | 1.0 | 0.15 | |
| WFD1915a...................... | 1 | 1.4 | 0.41 | 3 |
| WFD1917b...................... | 1 | −4.7 | 0.79 | |
| WFD1918b...................... | 1 | −3.4 | −0.73 | |
| WFD1920c...................... | 1 | 3.9 | 0.66 | |
| WFD1921........................ | 1 | −1.2 | 0.99 | |
| WFD1925........................ | 1 | −0.6 | −0.30 | |
| WFD1926a...................... | 1 | −0.4 | −0.73 | |
| WFD1927b...................... | 1 | 2.6 | 0.18 | |
| WFD1928a...................... | 5 | −0.1 ± 2.3 | 0.30 ± 0.26 | 4 |
| WFD1928d...................... | 2 | −0.2 ± 0.9 | 0.10 ± 0.47 | |
| WFD1929c...................... | 1 | −4.2 | 0.45 | |
| WFD1931........................ | 14 | −2.8 ± 6.9 | 0.39 ± 0.24 | 5 |
| WFD1933b..................... | 1 | 0.1 | 0.24 | |
| WFD1935........................ | 2 | −3.5 ± 4.0 | 0.16 ± 0.66 | |
| WFD1948........................ | 2 | 6.0 ± 2.1 | 3.16 ± 2.56 | 6 |
| WFD1949a...................... | 1 | −1.1 | −0.03 | |
| WFD1949b...................... | 2 | 2.3 ± 3.1 | −0.40 ± 0.20 | 7 |
| WFD1951a...................... | 1 | 3.0 | 0.43 | |
| WFD1953........................ | 6 | −0.2 ± 1.2 | 0.20 ± 0.46 | 8 |
| WFD1969........................ | 3 | −2.2 ± 3.6 | −0.12 ± 0.13 | 9 |
| WFD1985........................ | 1 | 0.6 | −0.48 | |
| WFD1997........................ | 7 | 0.9 ± 2.9 | 0.34 ± 0.40 | 10 |
| WFD2000........................ | 4 | −0.1 ± 2.3 | 0.21 ± 0.39 | |
| All transit circles......... | 62 | −0.7 ± 4.6 | 0.34 ± 0.84 | 11 |
| TMA2003........................ | 10 | −0.1 ± 0.5 | −0.22 ± 0.36 | 12 |
| All .............................. | 92 | −0.4 ± 4.1 | 0.24 ± 0.78 | 13 |

NOTES.—(1) Considering only wide ($\rho > 5''0$) systems, the mean ($N = 3$) residuals are $−0°6 ± 1°3$ and $−0''15 ± 0''19$. (2) Wide system ($N = 19$) residuals: $0°9 ± 3°0$ and $0''16 ± 0''42$. (3) Calibration data for close ($\rho < 5''0$) system only. (4) Wide system ($N = 2$) residuals: $2°5 ± 0°8$ and $0''02 ± 0''13$. (5) Wide system ($N = 8$) residuals: $1°5 ± 2°4$ and $0''40 ± 0''25$. (6) Wide system ($N = 1$) residuals: $8°0$ and $5''69$. (7) Wide system ($N = 1$) residuals: $−0°8$ and $−0''20$. (8) Wide system ($N = 5$) residuals: $−0°0 ± 1°2$ and $0''12 ± 0''45$. (9) Wide system ($N = 2$) residuals: $0°2 ± 1°3$ and $−0''07 ± 0''13$. (10) Wide system ($N = 3$) residuals: $1°3 ± 2°7$ and $0''16 ± 0''40$. (11) Wide system ($N = 41$) residuals: $0°1 ± 3°2$ and $0''33 ± 1''01$. (12) Wide system ($N = 8$) residuals: $−0°1 ± 0°5$ and $−0''12 ± 0''32$. (13) Wide system ($N = 68$) residuals: $0°3 ± 3°0$ and $0''24 ± 0''85$.



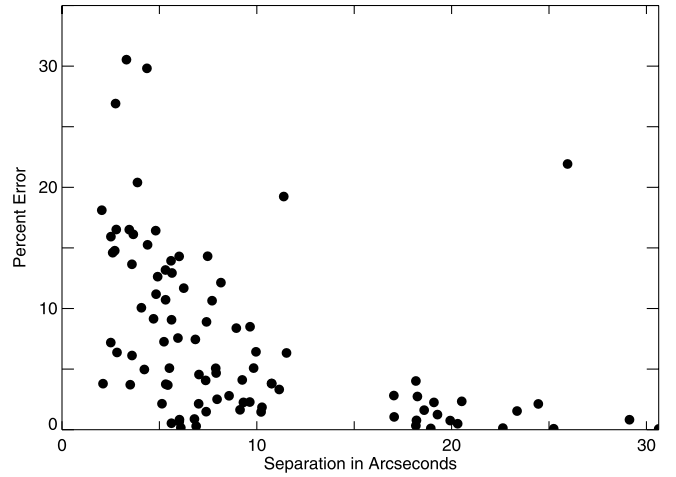FIG. 6.—Separation vs. percent error in separation $[|(O − C)_\rho|/\rho]$ for the measures listed in Table 3. At about $10''$ the error drops to ∼10%.
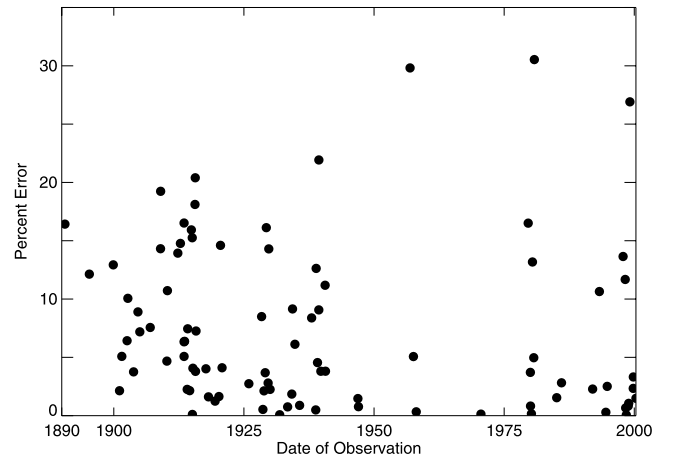


FIG. 7.—Date of observation vs. percent error in separation $[|(O − C)_\rho|/\rho]$ for the measures listed in Table 3. While the error seems to be increasing with time, this is primarily due to closer systems being measured.

TABLE 5
New WFC Doubles

| WDS or $\alpha$, $\delta$ (J2000.0) (1) | Discovery Designation (2) | Observation | | $N$ (5) | Position Angle | | Separation | | Magnitude | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | First (3) | Last (4) | | First (6) | Last (7) | First (8) | Last (9) | Primary (10) | Secondary (11) |
| 00099+7329 ........................... | WFC 1 | 1897 | 2000 | 5 | 30 | 36 | 7.1 | 6.4 | 10.38 | 10.41 |
| 00249−7716 ........................... | WFC 246 | 1894 | 1926 | 2 | 187 | 232 | 52.4 | 101.0 | 3.5 | 12.7 |
| 00251−8050 ........................... | WFC 2 | 1896 | 1999 | 7 | 137 | 139 | 6.2 | 6.0 | 10.81 | 10.92 |
| 00429+8002 ........................... | WFC 3 | 1897 | 2003 | 5 | 332 | 320 | 3.4 | 4.3 | 10.35 | 11.32 |
| 00453+6801 ........................... | WFC 4 | 1892 | 2003 | 5 | 336 | 334 | 4.3 | 4.5 | 10.78 | 11.80 |
| 00593+7712 ........................... | WFC 5 | 1897 | 1999 | 4 | 77 | 76 | 3.3 | 2.8 | 10.88 | 12.07 |
| 01151+3125 ........................... | WFC 248 | 1903 | 2002 | 6 | 5 | 9 | 10.2 | 10.6 | 11.73 | 11.73 |
| 01328+6911 ........................... | WFC 6 | 1894 | 2000 | 4 | 222 | 232 | 4.0 | 4.5 | 12.32 | 12.52 |
| 01452+3011 ........................... | WFC 249 | 1903 | 2001 | 4 | 97 | 95 | 9.7 | 10.3 | 12.06 | 12.18 |
| 02045+4750 ........................... | WFC 7 | 1898 | 1998 | 7 | 104 | 121 | 5.3 | 5.3 | 10.00 | 10.32 |

Note.—Table 5 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.

TABLE 6
WFC Contributions to Double Star Work

| Relative WFC Contribution | Number of Systems |
|---|---|
| WFC <1% of total.......................................... | 83 |
| 1% ≤ WFC < 10%........................................ | 1316 |
| 10% ≤ WFC < 50%..................................... | 15481 |
| WFC ≥ 50% ................................................ | 30127 |

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