Various Orbital Solutions and Double Star Statistics

Brian D. Mason
US Naval Observatory, 3450 Massachusetts Ave., NW, Washington, DC 20392, USA.
bdm@usno.navy.mil

Introduction

For the past twenty years, the primary double star observational technique utilized at the US Naval Observatory (USNO) has been speckle interferometry. Our two speckle cameras have been used on a variety of telescopes: our 26-inch in Washington, the Naval Observatory Flagstaff Station (NOFS) 61-inch, the McDonald Observatory 82-inch, the Mt. Wilson Observatory 100-inch and the twin 4 meter telescopes of Kitt Peak National Observatory (KPNO) and Cerro Tololo Interamerican Observatory (CTIO). While these instruments have each yielded many observations, they have been involved in rather different programs, with the 26-inch observing primarily the so-called "neglected" pairs and larger instruments conducting duplicity surveys and observing close, astrophysically interesting systems.
Although speckle is quite successful at resolving relatively close pairs, for those pairs which are both bright and very close long baseline optical interferometry may be the only option. Utilizing both the Center for High Angular Resolution Astronomy (CHARA) Array and the Navy Optical Interferometer (NOI), numerous hard-to-observe pairs first resolved by speckle have been observed using these arrays' superior resolution capabilities; this has allowed their orbits to be significantly improved; examples of pairs observed by each of these instruments are presented.
At the other separation extreme, a cache of photographic plates taken with the USNO double star camera has been digitized and processed. Some 66 plates of Sirius A and B taken between 1970 and 1984 have been reduced, which represents a 10% increase in the total number of published measures enabling a significant improvement over the current "best" Sirius orbit, almost one full revolution later.
Also presented are systems whose most recent solutions significantly contradict earlier ones and should serve as a warning to those who seek to compute solutions as soon as possible and also to those who might assume that just having a solution closes the book on a pair.
In addition to providing a summary of the current double star observing done by the USNO, statistics of the double star catalogs are presented.

1. Speckle Observing

1.1 *26-inch USNO DC*

The primary double star observational technique used by the USNO continues to be speckle interferometry. In 2001 we defined a new class of pairs as being "neglected" which are unconfirmed or have not been observed in ten or more years. The program on the 26-inch [1], (N, the number of resolved mean positions = 19,676) has concentrated on these pairs and service observing. The latter include especially bright pairs which are suitable for navigation or are on special lists prepared annually for the "Observer's Handbook" and the "Astronomical Almanac," as well as pairs whose predicted motion is relatively rapid during the calendar year. We also maintain a less complex secondary camera for use on the 26-inch [2], (N = 5044). On the 26-inch, the primary camera is capable of observing pairs with separations down to the Rayleigh limit of 200 milliarcseconds. With the secondary camera we rarely ventures below 1 arcsecond.

1.2 *Remote Observing*

Our primary speckle camera has also been used on the twin 4m telescopes at Cerro Tololo and Kitt Peak

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **OCT 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**
4. TITLE AND SUBTITLE **Various Orbital Solutions And Double Star Statistics**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Naval Observatory,3450 Massachusetts Ave., NW,Washington,DC,20392**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

For the past twenty years, the primary double star observational technique utilized at the US Naval Observatory (USNO) has been speckle interferometry. Our two speckle cameras have been used on a variety of telescopes: our 26-inch inWashington, the Naval Observatory Flagstaff Station (NOFS) 61-inch the McDonald Observatory 82-inch, the Mt. Wilson Observatory 100-inch and the twin 4 meter telescopes of Kitt Peak National Observatory (KPNO) and Cerro Tololo Interamerican Observatory (CTIO). While these instruments have each yielded many observations, they have been involved in rather different programs, with the 26-inch observing primarily the so-called ?neglected" pairs and larger instruments conducting duplicity surveys and observing close, astrophysically interesting systems.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

[3], (N = 2326), as well as the 100-inch telescope at Mt. Wilson Observatory [4], (N = 807), the 82-inch telescope at McDonald Observatory [5], (N = 621) and the 61-inch telescope of the USNO Flagstaff Station [6], (N = 656).

Typically, observing runs at larger telescopes have concentrated on systems of astrophysical interest. These include new discoveries and so called "problem stars" of the Hipparcos and Tycho surveys, orbit analysis pairs, and distinct sets: massive stars, red, white, and subdwarfs as well as a large survey of G dwarfs which included many exoplanet hosts.

1.3 *Orbits from Speckle Interferometry*

Speckle interferometry is especially well-suited for examining orbits at the operational limit of resolution by classical techniques, e.g., filar micrometry or eyepiece interferometry. An example of this would be "Tweedledum and Tweedledee." This is a pair of near identical interferometric pairs discovered by eyepiece interferometry ([7]; FIN 332). The similarity in brightness, separation and ambiguity led to many issues of misidentification as well as orbital quadrant ambiguities. It has been under regular observation by speckle inteferometry since the 1970s, most notably by CHARA and USNO.

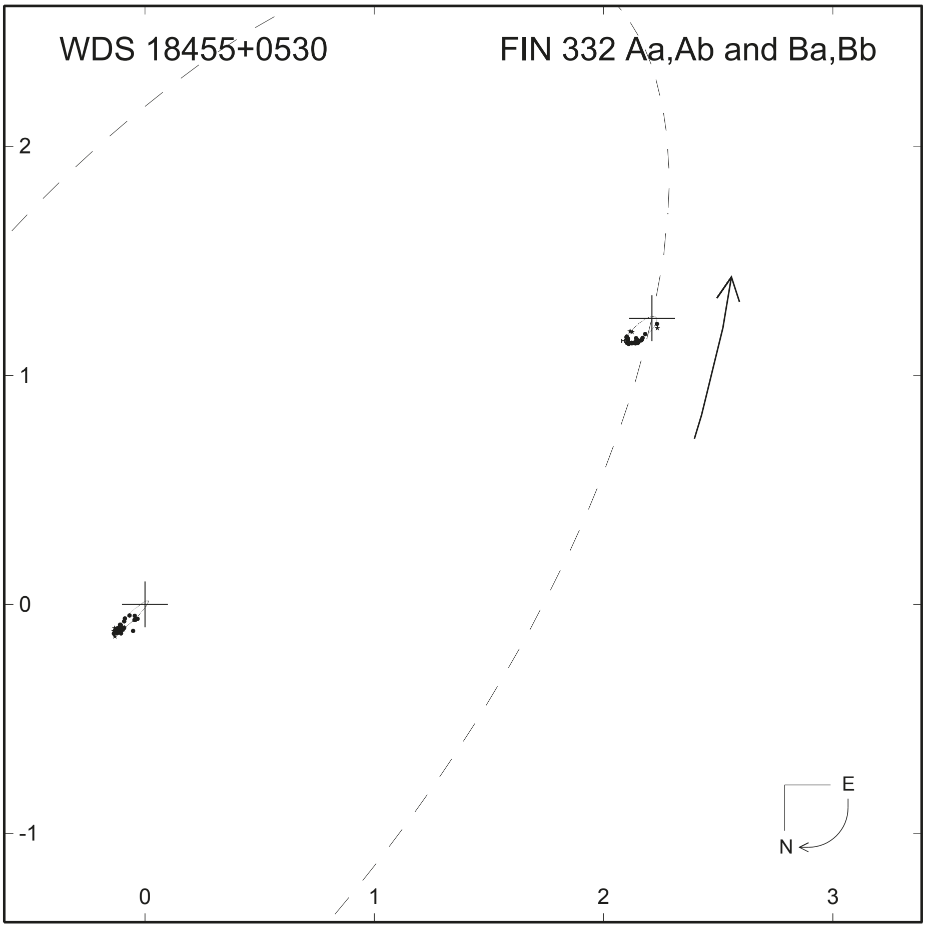

Figure 1: A "Ferris Wheel" plot of FIN 332 Aa,Ab and Ba,Bb, shown to the same scale as that of the wide pair, STF2375. In this plot the relative positions of STF2375 A and B are fixed and the dashed curve is indicative of the pair's orbital motion (although it has only moved 12° since its discovery in 1825, so no believeable orbital elements can be determined). The amount and direction of motion of the AB pair over the past 185 years are indicated by the thick curved arrow. The arrow at lower right indicates the direction of motion of both close pairs, which is opposite that of the wide pair. Scales are in arcseconds.

Continued observations have allowed quadrant and identification issues to be solved and for precise orbits to be determined. The pairs have a coplanarity value, ϕ, of $25.^{\circ}2 \pm 12.^{\circ}2$ degrees. According to the Fekel [8] definition they are within 1σ of being coplanar. For further details on this interesting system see [9].
In order to observe different objects or the same objects with different capabilities we have an active collaboration with Andrei Tokovinin; we most recently worked with him and HRCam on the 4.1m SOAR telescope and observed 1246 pairs [10]. Some of these orbits include astrometric pairs, whose orbits were first determined from periodic errors in position and proper motion. A new solution for LAF 27 (κ For) was found by fixing the period and eccentricity to the astrometric orbit [11] values; the resulting orbit gives expected masses. This is a system where *a priori* information is essential. On the other hand, the CHR 238 (HIP 42916) solution was determined independently, but has consistent elements: $P = 815d, e = 0.68$ [12], (astrometric orbit); $P = 824.7d, e = 0.671$ (resolved orbit). See Figure 2.

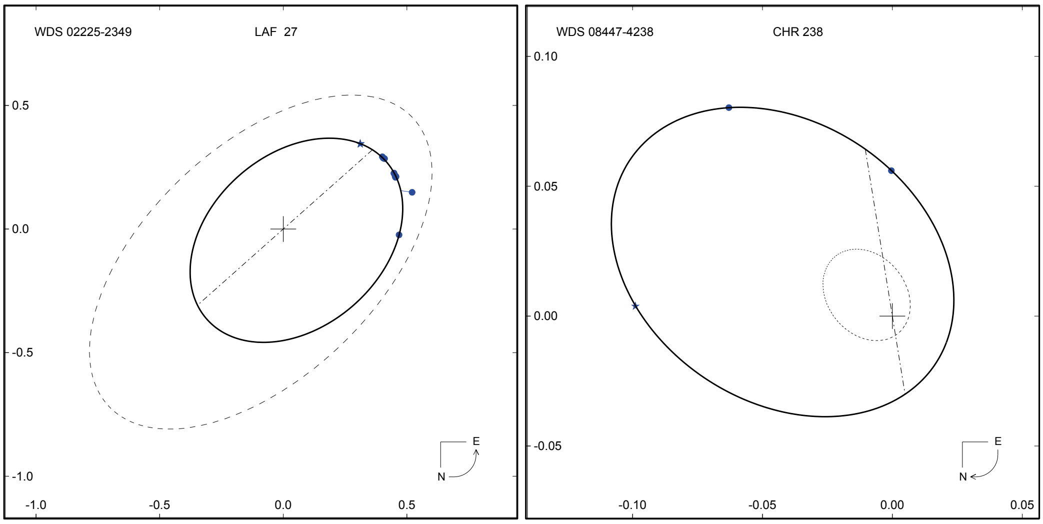

Figure 2: Relative orbits of LAF 27 (*left*) and CHR 238 (*right*). In these orbits the dashed line are published astrometric orbits as cited in the text, so should appear as a scaled version of the relative orbit.

2. Optical Interferometry

As speckle interferometry has proved quite advantageous especially in observing pairs at the capability limit of earlier techniques, optical interferometry is a technique well-suited for exploiting objects near the capability limit of speckle interferometry. The USNO has utilized two different optical interferometers for observing these pairs.

2.1 *Navy Optical Interferometer*

The Navy Optical Interferometer (NOI) is located on Anderson Mesa, outside Flagstaff in Northern Arizona (USA). The current operational baseline allows routine observing to a resolution of 1 mas, ultimately this capability will be 200 μas. This R to V band instrument has a current limit of V$\sim$6. This will be extended significantly when the former Keck Interferometer outrigger telescopes (1.8m) are integrated into the system.
Six-way beam combination is now routinely generating the typical measureables of resolved systems, ρ

and θ, making it ideal for combining with historical binary star data.
Focusing primarily on hot dwarf/cool giant combined solution orbits (e.g., [13]), these pairs and others like them are under observation with the NOI at present. A new solution based on available relative astrometry and radial velocities [14] is shown in Figure 3 (*left*).

2.2 *CHARA Array*

The CHARA Array, on Mt. Wilson in California, is an interferometer similar in configuration to the NOI. The emphasis on achieving results on the longest baselines in infrared makes this instrument capable of higher resolution than the NOI. However, at present most results are pairwise and give the interferometer observables of baseline and visibility. A recent innovation utilizing Separated Fringe Packets (SFP, [15]) produces measures of ρ and θ, which can be combined easily with other data. An example of a system under analysis here is HD 178911. While the orbit [16] of HD 178911 seems superficially adequate, only six relative astrometric measures were available at the time, leading to larger than desired errors: M_A = 1.07±0.37 $M_\odot$, M_B = 0.84±0.29 $M_\odot$, π = 25±8 mas. The significantly greater number of points, most of which are from CHARA SFP, yields combined solution results of M_A = 0.736±0.049 $M_\odot$, M_B = 0.572±0.047 $M_\odot$, π = 29±2 mas. The masses are at the 1σ extreme of the earlier solution. The Hipparcos parallax error (π = 19±2 mas) may be due to the orbital motion not being taken into account. See Figure 3 (*right*).

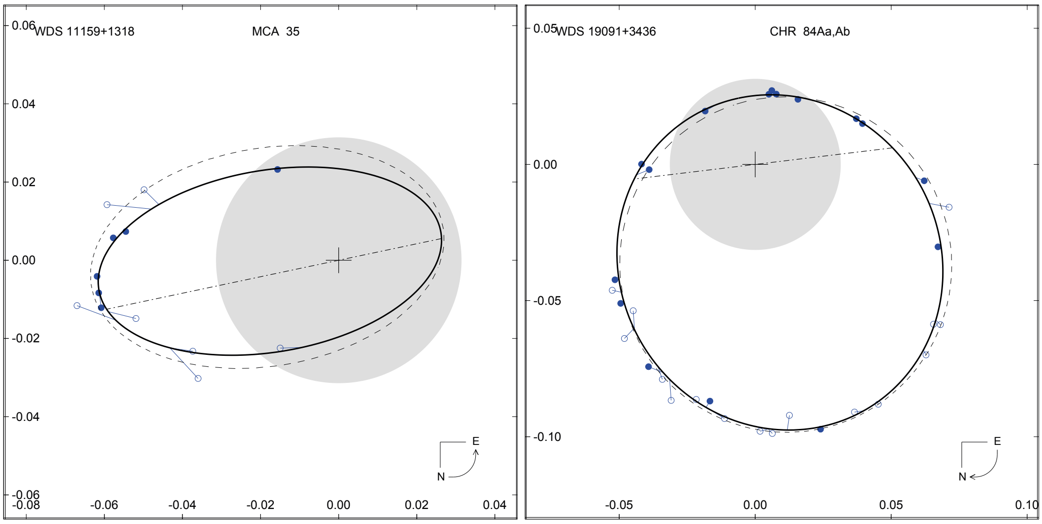

Figure 3: *At left* is the relative orbit plot of HR 4365 = WDS 11159+1318. In the plot the solid curve is the new orbit, while the dashed curve is the orbit from [13]. The open circles are measures from speckle interferometry while the solid circles are the new measures from the NOI. Data points are connected to their predicted position by O−C lines. The large shaded circle centered on the origin is the resolution limit of a 4m telescope. The right and bottom margin give the scale of the plot in arcseconds and the orientation and direction of motion is indicated at lower right. *At right* is the new orbit of HR 7272 = WDS 19091+3436 along with the orbit of [16]. All symbols are as in the figure at left, except now the filled circles are separated fringe packet measures [15] obtained with the CHARA Array.

3. Photographic Data: Sirius

At the other separation extreme, a cache of photographic plates taken with the USNO double star camera mounted on the 26-inch telescope have been digitized and processed, using the method described in [17]. Some 66 plates of Sirius A and B taken between 1970 and 1984 (10% of the total currently available), have been reduced. They enable a significant improvement over the current “best" Sirius orbit [18], almost one full revolution later. See Figure 4.

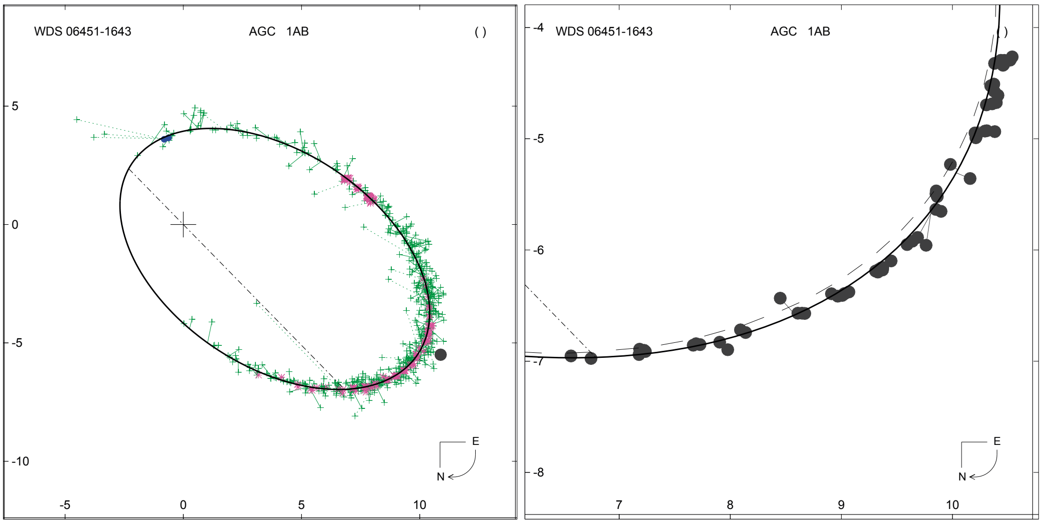

Figure 4: The new photographic solution of Sirius. Final analysis of this solution is currently in progress.The dashed curve is the orbit of [18]. The region where most of the new data was obtained is shown in a zoom of the orbit at right.

4. Premature Solutions

One of the long term goals of the study of visual binaries is their kinematic solution, whether it is orbital or linear. Shortcomings of premature solutions are illustrated in Figure 5. In the left figure, CHR 153, an orbit of 72.3 years was calculated in 2003 [19] based on only three data points. Subsequent observations in 2005, 2008 and 2010 exhibited a trend in orbit residuals. The system is better fit by a linear solution, indicating the pair is likely optical. The counter example, on the right, is STF 147. A linear solution first seemed likely for this pair; however, more recent observations had large, systematic residual offsets and now the data are fit much better with an orbital solution, albeit premature.

5. Double Star Catalogs and Statistics

The Washington Double Star Catalog [20] has been the official repository of double star observations for IAU Commission 26 since the General Assembly of 1964 [21]. As of 1 October 2011 the WDS contained 772,221 mean positions of 115,422 pairs. However, the systems that are most well known are the brightest pairs, many of which Gaia will be unable to observe. The overall statistics of various magnitude bins are shown in Table 1.

In the initial charge to Lt. Matthew Fontaine Maury, first superintendent of the U.S. Naval Observatory

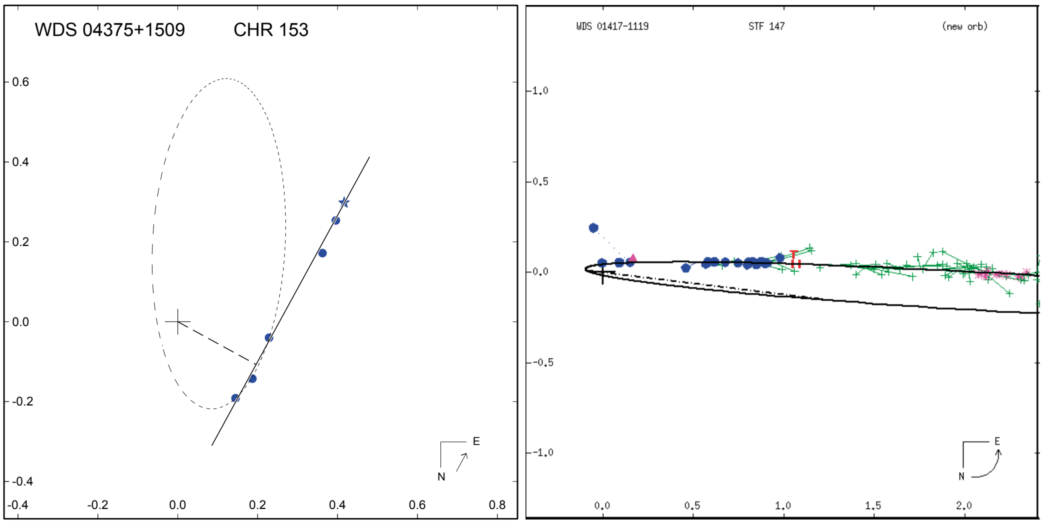

Figure 5: Examples of premature solutions. At *left* is a premature orbital solution to a likely linear pair, CHR 153. At *right* is STF 147, a pair first characterized as linear, but more accurately fit by Keplerian motion.

Table 1: Catalog Statistics

Sample	Number Systems	Number Measures	Measures per System	Number Orbit	Number Linear	Percentage Solution
Whole Catalog	115,422	772,221	6.69	1653	1261	2.5
$0.50 < V < 6.00$	3,596	104,334	29.01	301	152	12.6
$6.01 < V < 12.00$	87,832	613,874	6.99	1312	1089	2.7
$12.01 < V < 20.00$	23,798	52,067	2.19	34	16	0.2

in 1846, double stars were specifically mentioned as objects to be observed by the USNO. At various levels of industry and by multiple techniques we have continued observing double stars since that time. Half-a-century ago we added maintenance of the double star database to our retinue of tasks. Our work in all these areas continues.

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