

THE 2001 US NAVAL OBSERVATORY DOUBLE STAR CD-ROM. II. THE FIFTH CATALOG OF ORBITS OF VISUAL BINARY STARS

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ABSTRACT

The Fifth Catalog of Orbits of Visual Binary Stars continues the series of compilations of visual binary star orbits published by Finsen, Worley, and Heintz from the 1930s to the 1980s. As of 2001 January 1, the new catalog includes 1465 orbits of 1430 systems. All orbits have been graded as in earlier catalogs, although the grading scheme has been modified to be more objective. Ephemerides are given for all orbits, as are plots including all associated data in the Washington Double Star 2001.0 database. A subset of orbits useful for scale calibration is also presented. This catalog is one of four USNO double star catalogs to be included on a new CD-ROM.

Key words: binaries: general — binaries: visual — catalogs

1. INTRODUCTION

The Fifth Catalog of Orbits of Visual Binary Stars (Hartkopf, Mason, & Worley 2001a) continues the series of compilations of visual binary star orbits previously published by Finsen (1934, 1938), Worley (1963), Finsen & Worley (1970), and most recently by Worley & Heintz (1983), in their Fourth Catalog of Orbits of Visual Binary Stars. The successor to the Fourth Catalog was to have been the retirement project of Charles Worley, but these plans were thwarted by his untimely death on New Year's Eve 1997, just days before his scheduled retirement date. We (W. I. H. and B. D. M.) have attempted to continue Charles's project with the care and thoroughness he brought to all his astronomical endeavors.

The 17 years since the publication of the Fourth Catalog have seen revolutionary changes in the field of visual double star work, primarily through the advent and maturation of interferometry. Speckle interferometry, especially on large telescopes, can produce astrometric results of very high accuracy (down to the milliarcsecond level), even for systems much closer and of shorter period than those available to micrometry and other visual techniques. Although the speckle technique has been known since 1970, it did not produce data in significant quantity until about 1975; at the time of publication of the Fourth Catalog, only a handful of orbits had been calculated in which speckle played much of a role. Now, however, speckle interferometry is a mature field, and nearly all orbits published since the 1980s have included speckle results, some exclusively. Long-baseline interferometry (e.g., Mark III [cf. Pan et al. 1990] and the Navy Prototype Optical Interferometer [NPOI; cf. Hummel et al. 1998]) is now perhaps in a similar degree of maturation as was speckle in 1983; an increasing number of binaries once exclusively the “property” of spectroscopists are now the targets of multiaperture telescope arrays. Indeed, the distinction between the *spectroscopic* and *visual* regimes will largely disappear in the coming decades, as the magnitude sensitivity of these new interferometers improves. Catalogs such as this will have to evolve as well; as spectroscopic and visual “combined solutions” go from

being rare to commonplace, the argument for publishing only a subset of a binary's elements will grow increasingly artificial. For the present, however, information on combined solutions is relegated to a notes file.

2. GRADING THE ORBITS

A major consideration in the production of a new catalog is the determination of grades for each orbit. The Fourth Catalog grading scheme was based on orbital coverage, number of observations, and their overall quality and was presented on a numerical scale (1 = definitive to 5 = indeterminate; see Fig. 1 for examples) based on the accumulated experience of the authors and their qualitative assessment of individual observers. (It should be noted that Worley & Heintz had some six decades' worth of experience at the time they published the Fourth Catalog; these two gentlemen also rank as the third and second most prolific binary star observers of all time.) While useful for judging the reliability of a given orbit, this scheme was rather subjective and, therefore, difficult to duplicate by catalogers with less experience. We attempted to devise a more objective grading scheme, based on the same information as that available to Worley & Heintz.

2.1. Evaluating the Observations

In order to determine rms residuals, we first must determine relative weights to be assigned to each observation. The following factors were considered:

1. Telescope aperture.
2. Binary separation.
3. Magnitude and magnitude difference.—Since we are mainly interested in relative weights to be assigned for observations of a given binary, these factors are presumed constant and we have ignored them.
4. “Number of nights.”—Some observers publish individual measures, while other average two or more into means. A simple $\sqrt{N}$ term handles this.
5. Expertise of the observer.—This is the most difficult factor to evaluate. Accuracy should improve with experience but may decrease as, for example, a visual observer's eyesight deteriorates with age (some observers produced measurements for 40, 50, and even 70 years). We have ignored this age factor for the present, however.

¹ Deceased.

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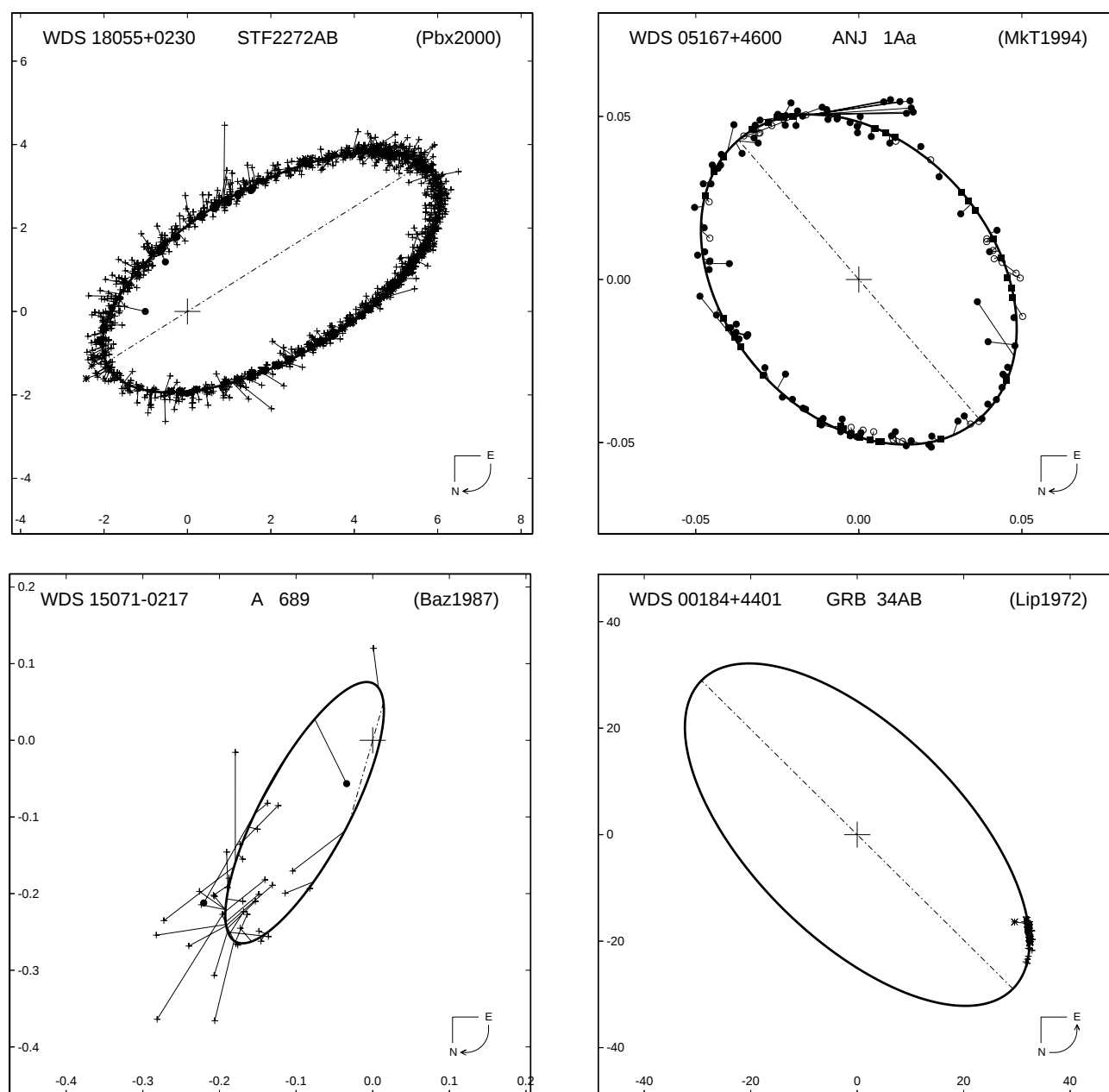


FIG. 1.—Two examples each of grade 1 (*top*) and grade 5 (*bottom*) orbits. Factors used in determining these grades are discussed in the text. In this and all other figures in the Fifth Catalog, plus signs indicate visual (micrometric) observations, asterisks photographic measures, and other symbols various interferometric techniques (open circles, filled circles, and squares for eyepiece interferometry, speckle or other single-aperture techniques, and multiaperture techniques, respectively). Finally, an “H” or “T” indicates a measure from *Hipparcos* or *Tycho*. The dot-dashed line indicates the line of nodes. Scales are in arcseconds, and the curved arrow at lower right indicates the direction of orbital motion. An identification line at the top of each orbit lists the WDS designation (i.e., approximate epoch 2000 coordinates), the discoverer designation, and a reference code for the orbit.

6. Other factors, such as systematic errors in a given piece of equipment, quality of the scale calibration, seeing conditions at a given site, etc.—These are ignored as separate factors but obviously are part of the “observer expertise” factor.

The best method we really have for evaluating the quality of an observation is to see how it compares with others. In practical terms, this means that we examine the size of the orbit residuals it gives. Here we unfortunately are stuck with a bit of a circular argument: In order to assign weights to observations, we must compare them with orbits. Yet in order to determine those orbits in the first place, we must

assign weights to the observations! The way in which we chose to minimize this problem was by sheer force of numbers—by examining many well-observed binaries whose orbits are generally acknowledged to be of high quality.

All grade 1 and 2 orbits from the Fourth Catalog were examined, together with all more recently published orbits and numerous long-period orbits (such as GRB 34 in Fig. 1). This last group was included in order to evaluate observers of wider systems. Many of these systems show small orbit residuals over the covered orbit arc, although the lack of phase coverage earns them a poor grade. From ~ 750 orbits and over 100,000 observations initially examined,

some 450 orbits and $\sim 66,000$ observations were chosen for evaluation of observer weights.

Since the number of “degrees of freedom” is large, we simplified the problem in two ways:

1. Since binary resolution is a function of telescope aperture, we remove this complication by scaling separation to the Rayleigh limit of the telescope used ($\rho_{\text{lim}} \sim \lambda/D$, where λ is the wavelength and D is the telescope diameter; assuming $\lambda = 550$ nm, $\rho_{\text{lim}} \approx 0.136/D$, for ρ_{lim} in arcseconds and D in meters).

2. Different observing techniques—micrometry, photography (including conventional CCD observations), and interferometry (plus adaptive optics, satellite observations, and other high-resolution techniques)—were evaluated separately. All data for a given technique were first studied, and then relative weights for observers using that technique were determined.

Figures 2 and 3 illustrate some of our initial findings on accuracy versus separation for the different techniques. Both θ and ρ residuals show obvious dependence on separation. The long-known fact that separations of very close systems are systematically overestimated is also apparent, especially in the left panel of Figure 2. Assuming that $(d\rho/\rho)^{-2}$ gives a reasonable estimate of the relative weight of an observation, we fit a polynomial to $(d\rho/\rho)^{-2}$ versus ρ/ρ_{lim} for each technique to determine this first weighting factor as a function of separation and telescope aperture.

As a second step, we wish to determine the relative qualities of each observer who uses a given technique. We do this by removing the overall error versus separation fit derived above, then determining rms residuals for each observer. Observers having too few measures for individual weighting are averaged together. Relative weights for each observer are then defined as the inverse square of their rms residual (with the weighted mean weight for each technique scaled to 1). We find as follows:

1. Visual observers received a wide range in relative weight, from about 0.1 to 4.5. It must be noted that this is not really a measure of an observer’s competence; a person who only looks at bright, wide, low zenith distance, small-

Δm pairs will tend to receive a better grade than does someone who pushes his instrument to its limits in magnitude, Δm , etc. These more difficult observations are usually the more important, however.

2. Photographic observers were of fairly uniform quality. Observers having significant numbers of measures ranged in relative weight from about 0.5 to 1.4, while the observers making smaller contributions received a weight of 0.3. Since photographic techniques are presumably somewhat more objective than visual measurement, this finding seems reasonable.

3. Eyepiece interferometry tends to get rather low marks (0.01–0.3) compared with other interferometric techniques. Speckle and other single-aperture techniques garnered weights of 0.02 to 1.4, with the larger speckle efforts generally receiving the higher weights. The Mark III received a comparable weight of about 0.9. NPOI received a very high weight (13.3), but this is rather misleading, as the number of measures is small and the separation regime of this instrument is such that this is largely an indication of internal consistency.

As mentioned earlier, the third factor is simply the $\sqrt{N}$ term, which gives higher weight to normal points averaged from more than one observation. Finally, a few measures in the Washington Double Star Catalog (WDS) are flagged as being uncertain or of poor quality. The term W_{quality} , usually assigned a value of unity, is reduced by half for such measures. The overall weight of a given observation, then, is determined by the product of these four terms:

$$W = W_{\text{technique}}(\rho, \text{aperture}) W_{\text{observer}} \sqrt{N_{\text{measures}}} W_{\text{quality}}.$$

2.2. Evaluating the Orbits

Worley & Heintz used the following criteria for each orbit grade (as quoted from the Fourth Catalog):

- | | |
|----------------|---|
| 1 = Definitive | Well-distributed coverage exceeding one revolution; no revisions expected except for minor adjustments. |
| 2 = Good | Most of a revolution, well observed, with sufficient curvature to give considerable confidence in the |

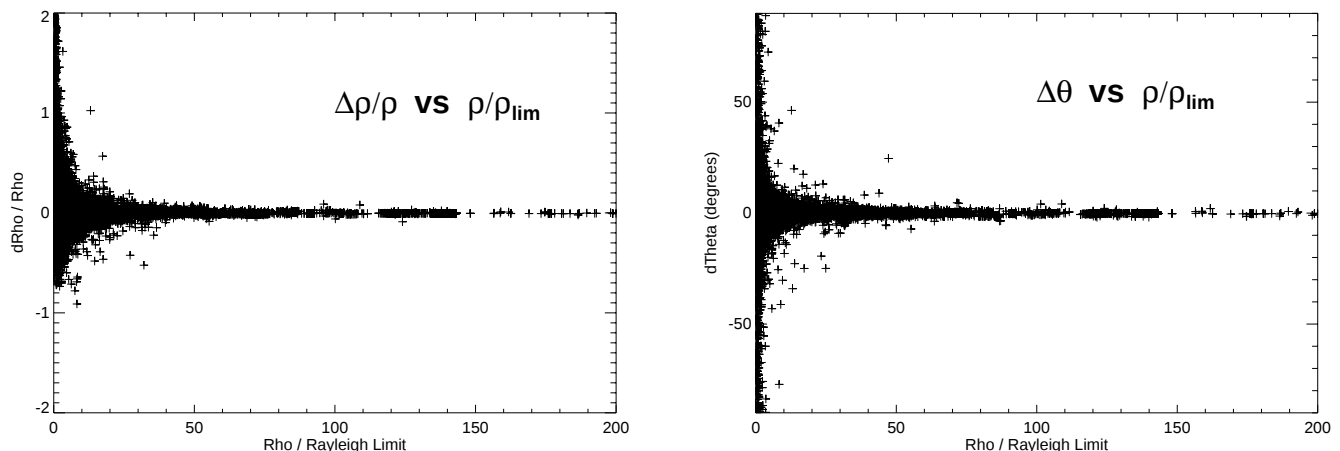


FIG. 2.—O—C errors in relative separation and position angle, vs. separation (scaled to each telescope’s Rayleigh limit). Note the systematic overestimate of separation at small values of ρ , seen in the left panel.

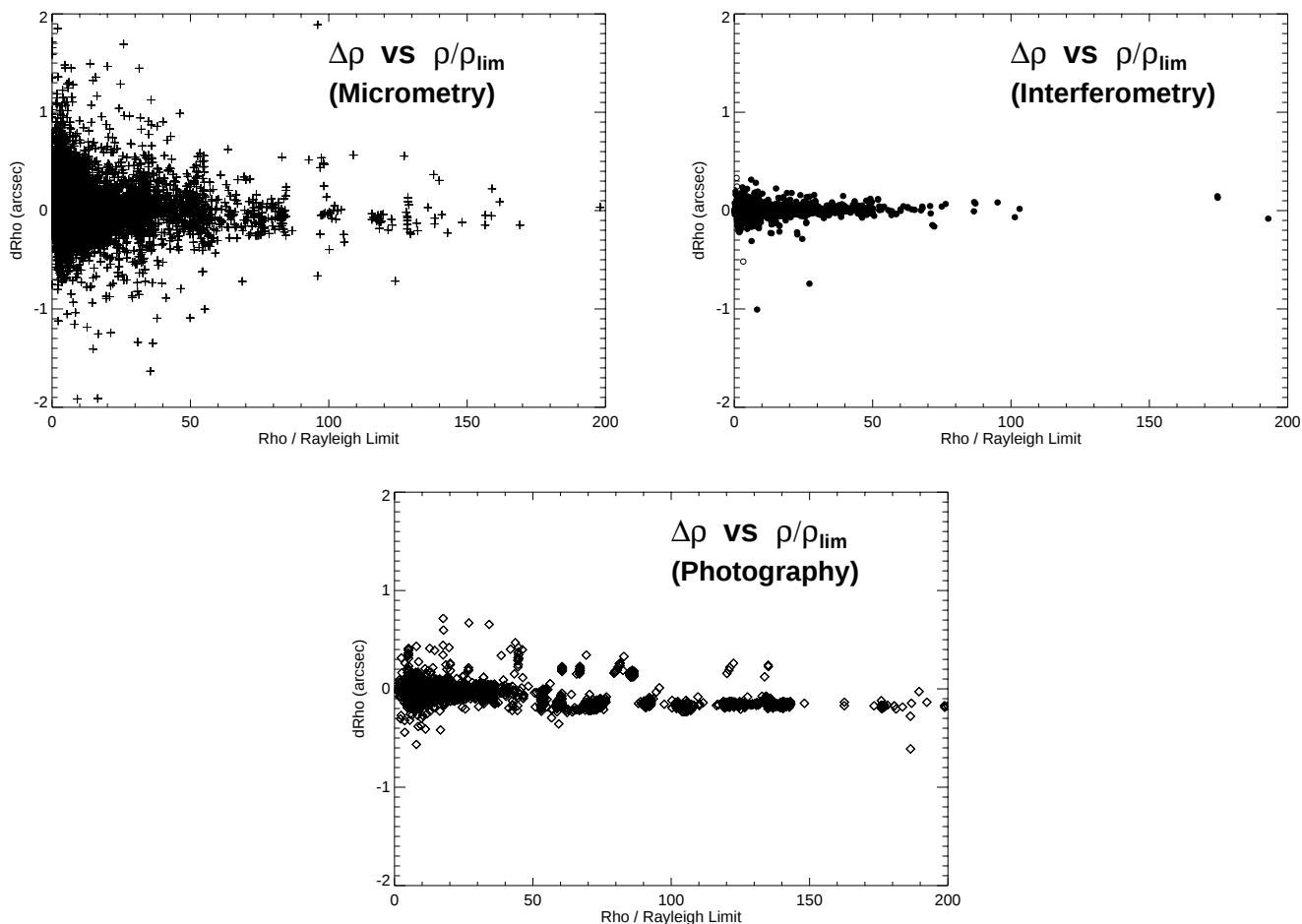


FIG. 3.—O — C separation errors vs. separation, for visual, interferometric, and photographic observing techniques. The relative accuracies of the three techniques are apparent.

- derived elements. No major changes in the elements likely.
- 3 = Reliable At least half of the orbit defined, but the lesser coverage (in number or distribution) or consistency of the data leaves the possibility of larger errors than in Grade 2.
- 4 = Preliminary Individual elements entitled to little weight, and may be subject to substantial revisions. The quantity $(3 \log a - 2 \log P)$ should not be grossly erroneous. This class contains: orbits with less than half the ellipse defined; orbits with weak or inconsistent data; orbits showing deteriorating representation of recent data; ...
- 5 = Indeterminate The elements may not even be approximately correct. The observed arc is usually too short, with little curvature, and frequently there are large residuals associated with the computation.

How can these grades be determined in an objective manner? We evaluated as many of the 928 orbits in the Fourth Catalog as possible, as follows: We extracted from

the WDS the $\sim 100,000$ observations made of these objects through 1982 (i.e., the same data available to Worley & Heintz for their evaluations). After removing orbits without grades, plus a few problematic orbits and obviously erroneous measures, we were left with 901 orbits and 93,775 observations. We then determined the following statistical factors for each system:

1. Weighted rms residual in separation (dR);
2. Weighted rms residual in relative separation (i.e., dR/R);
3. Theta coverage—measures were sorted in order of θ , and then the rms difference in angle [i.e., $\theta(n) - \theta(n-1)$] was calculated;
4. Maximum “gap” in θ —also from above θ -sort;
5. Phase coverage—calculated from period (P) and periastron epoch (T), then sorted and rms differences determined as done with θ ;
6. Maximum “gap” in phase;²
7. Number of revolutions from first to last observation;
8. Total number of observations.

² Why analyze both θ and phase coverage? While both position angle and phase are equivalent for a circular, face-on orbit, position angle coverage becomes increasingly meaningless for inclinations approaching 90° , while uniform phase coverage may undersample periastron passage for a high-eccentricity orbit.

Some of our results are shown in Figure 4. Data for each grade are spread over three lines in order to more easily see individual points. Means are listed below the data for each grade, with vertical lines indicating mean and 1σ values. “Outliers” (removed from the statistics) are plotted with smaller symbols.

As is apparent in both the orbit examples in Figure 1 and the Figure 4 results, no one factor alone is sufficient for determining the grade. For example, some poorer orbits show very small separation residuals (as evidenced by the turnover in the rms dR/R plot for grades 4 and 5); the extremely long period (and resulting poor orbit coverage) determines their grade. Others have shorter periods, and thus good coverage, but are close and difficult to measure, yielding large separation residuals.

Simple polynomial fits were made between each set of means and their corresponding grades, and the best fit to the Fourth Catalog grades was found by averaging results for the number of observations, the number of revolutions, the maximum angle and phase gaps, and the weighted rms separation residual. New grades were then calculated for each of the 901 orbits based on all these factors; Figure 5 illustrates the degree of correlation between our new, “objective” grades and the Fourth Catalog originals. Some 98% of the grades matched to within one grade level. A check of those systems where our grades disagreed by more than one grade found that in nearly all cases the Fourth Catalog grades appeared to be in error. It therefore appears that our quantitative method for grading orbits gives a reasonably good match to Worley & Heintz’s originals.

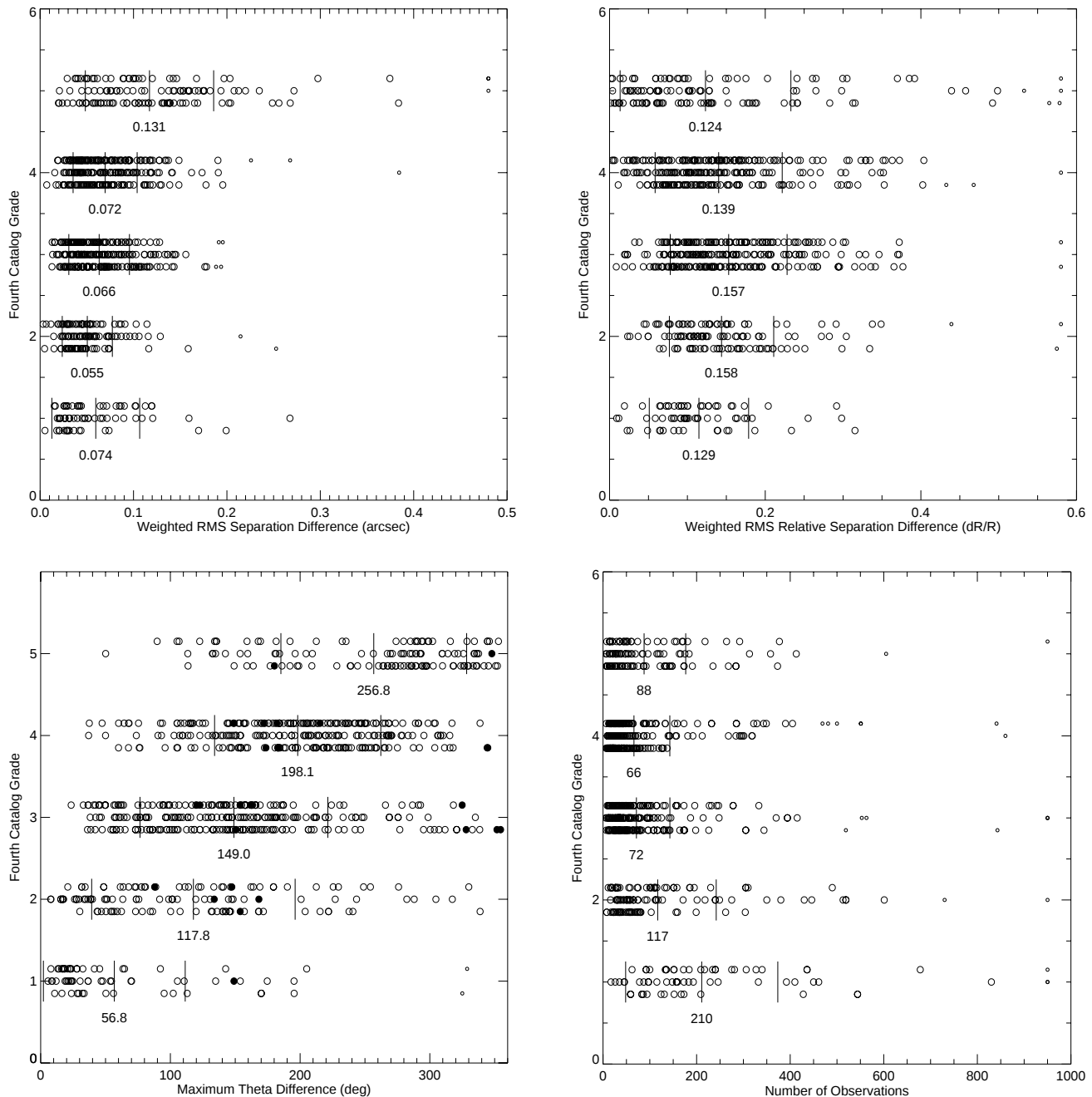


FIG. 4.—Fitting Fourth Catalog grades to rms residuals and other factors, as described in the text

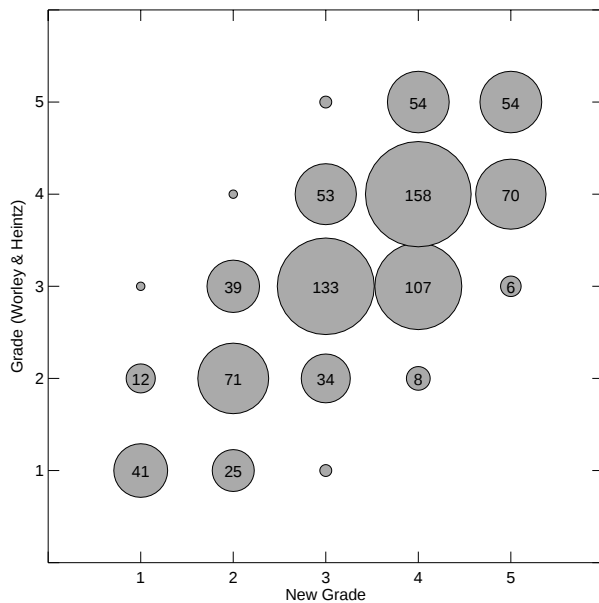


FIG. 5.—Comparison of grades determined by the method described here with those determined by Worley & Heintz. Circle sizes are scaled to the corresponding number of orbits with these grades; the numbers themselves are given inside all but the smallest circles, where N is only 1 or 2.

One last adjustment was made before grades were determined for all orbits. Thanks to the higher astrometric accuracy achievable by interferometric techniques, we now have the ability to determine orbital elements with higher accuracy than previously considered possible. Since an old “grade 1” orbit may no longer be considered *definitive*, we have applied a “grade deflation” factor by modifying our polynomial fits somewhat. The factors we applied are as follows:

- old grade 1 $\rightarrow$ new grade 1.4 ,
- old grade 2 $\rightarrow$ new grade 2.3 ,
- old grade 3 $\rightarrow$ new grade 3.2 ,
- old grade 4 $\rightarrow$ new grade 4.1 ,
- old grade 5 $\rightarrow$ new grade 5.0 .

It is worth noting that combined astrometric-spectroscopic solutions are graded only on the number, quality, and distribution of their differential astrometric measures. These solutions typically have P , T , e , and ω (or at least a subset of these elements) known to higher accuracy than is reflected in only the visual data.

A handful of orbits could not be graded, because of a lack of ρ and θ measures in the WDS. The first class of these are the few interferometric binaries observed by the Mark III or the Palomar Testbed Interferometer (e.g., Boden et al. 1999), for which only visibilities were published. These orbits, given a grade of “8” in the catalog, are usually of quite high quality. More common are astrometric orbits, which receive a grade of “9”; these orbits tend to give rather poor fits to any later resolved measures.

A final note: we do not consider this grading method optimum; a visual inspection of competing orbits is still necessary if their grades are within a few tenths of each other. Other schemes, such as the “efficiency” technique of

Eichhorn (cf. Eichhorn & Cole 1985), will be investigated in the future. For the present, however, we think this method gives reasonably reliable results.

3. DESCRIPTION OF THE CATALOG

The “master file” for the Fifth Catalog³ includes all sets of orbital elements in the Fourth Catalog, as well as all subsequently published orbits either tabulated by Worley or found through searches of the literature from 1980 through 2000. This file included 3494 orbits of 1430 systems as of the 2001 January 1 cutoff date. All orbits were graded, and only those judged of highest grade for each system were included in the published Fifth Catalog. If two orbits for a given system were judged to be of nearly identical quality, the earlier published orbit was chosen for the catalog (although both are kept if the orbits were contemporaneous). A few systems were found to have two very different sets of orbital elements that yielded comparable grades; in these cases both orbits were included. These “special cases” bring the total number of orbits in the Fifth Catalog to 1465.

The World Wide Web allows much more flexibility than is available in a paper catalog such as the Fourth Catalog, so we have added several extra columns of information, as well as figures and ephemerides. Names and orbital elements for a given system are tabulated on a single line (for ease in reading, sorting, etc.), so in order to allow all essential information to fit on a single screen width, secondary information was relegated to an “ephemeris file” that is linked to the main file. Columns in this main table are as follows:

1. Coordinates.—International Celestial Reference System epoch 2000.0 right ascension and declination, usually given to 0^h.1 accuracy in right ascension and 1" in declination. Coordinates were extracted from SIMBAD and so are mostly based on *Hipparcos* values.
2. WDS designation.—Many of these coordinates (given to 0^m.1 and 1") were generated by precessing lower precision B1900 positions to J2000; therefore, the WDS designations may vary slightly from the coordinates in column (1).
3. Discoverer designation and components involved.—If no components are listed, the orbit is of the AB pair.
4. ADS (Aitken double star catalog) number.
5. HD (Henry Draper catalog) number.
6. *Hipparcos* number.
7. Magnitude of the A component.—A letter “v” following the value indicates a star of variable magnitude.
8. Magnitude of the B component.—Variable magnitudes are indicated as in column (7).
9. The period (P), in years.
10. The semimajor axis (a), in arcseconds.
11. The inclination (i), in degrees.
12. The node (Ω), in degrees.—An identified ascending node is indicated by an asterisk following the value.
13. The time of periastron passage (T).
14. The eccentricity (e).
15. The longitude of periastron (ω), in degrees, reckoned from the node as listed.
16. A code for the reference (usually based on the name of the first author and the date of publication), with a link to a reference file.

³ See <http://ad.usno.navy.mil/wds/orb5.html>.

17. The grade (to the nearest integer), as previously discussed.

18. A link “N” to any notes for this system. Alternatively, an “e” indicates that the reference includes errors for individual orbital elements.

19. A link “P” to a figure illustrating the orbit and all data for this object currently tabulated in the WDS database. Symbols used in these figures are as in Figure 1.

20. A link “E” to appropriate entries in the ephemeris file.

Columns in the ephemeris file are as follows:

1. The WDS designation, as above;
2. The discoverer designation, as above;
3. The orbit grade, as above;
4. The reference code, as above;
5. The equinox, if any, to which the node refers;
6. The date of the last observation used in the orbit calculation, when given;
7. Inclusive dates for which an ephemeris is given by the author; and
8. Predicted values of θ and ρ for the years 2000–2004.

4. CALIBRATION SYSTEMS

A subset of systems from the Fifth Catalog was prepared in answer to requests for lists of binaries that might be used for scale calibration purposes. Stars initially picked for this list included most of the “grade 1” orbits; these are systems having many observations (usually covering more than one orbital revolution), good phase coverage, and small separation residuals. These tend to be closer, shorter period systems, in some cases resolvable only by large telescopes or multiaperture interferometers. In order to provide calibrators for smaller instruments, a similar number of wider, long-period systems were chosen as well. Orbital coverage for these wide systems is incomplete, so most were given grades of only 4 or 5; however, since orbital motion is slow, the quoted elements should predict the stars’ motions quite well for many years into the future.

This subset of the Fifth Catalog presently includes 81 orbits of 80 systems. As in the main catalog, figures are included in order to allow the user to visually inspect each orbit’s quality prior to use. An expanded set of ephemerides

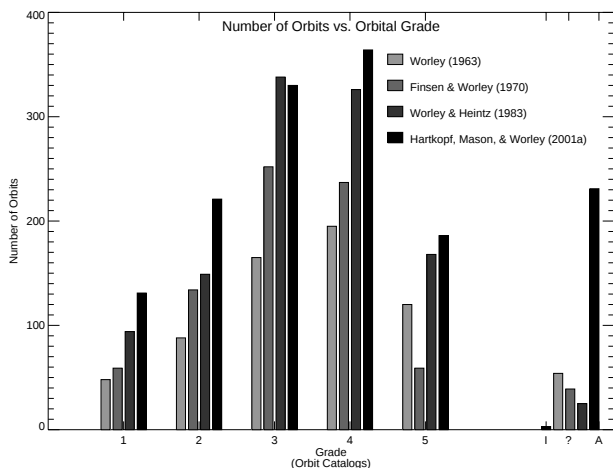


FIG. 6.—Distribution of orbits with grade for the Fifth Catalog and three earlier catalogs. Ungraded astrometric and interferometric orbits are tallied in the rightmost columns.

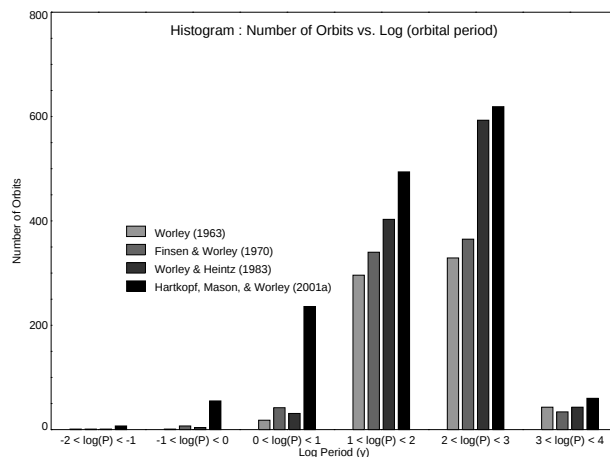


FIG. 7.—Distribution of orbits with period. While we see the expected increase in number of orbits for all period regimes, the most dramatic increase is apparent at shorter periods. The efforts of interferometric techniques such as speckle and, now, arrays are beginning to bear fruit, and we are seeing a greater overlap into what has traditionally been the spectroscopic period regime. This is heartening news to anyone involved in the determination of stellar masses.

has also been generated, giving predicted separations and position angles with finer time resolution than in the main catalog (although these ephemerides will obviously still be of little use for very short period systems).

Note that all “calibration candidate” orbits are *not* of the same quality. Before adopting a set of elements, it is recommended that users examine the elements, figures, etc., carefully to check whether that orbit appears to be of proper scale and sufficient quality for their purposes. Also, using measurements of double stars to calibrate the measurement of other double stars is certainly circular (or, if you will, Keplerian). We strongly advocate the use of other absolute calibration techniques such as a slit mask (cf. McAlister et al. 1987; Hartkopf et al. 1997; Douglass, Hindsley, & Worley 1997) or at least star trails (for east-west orientation) if at all possible. When double stars are necessary for scale calibration, the set provided should be adequate; however, the measures determined will only be as accurate as the calibration systems used. The use of these

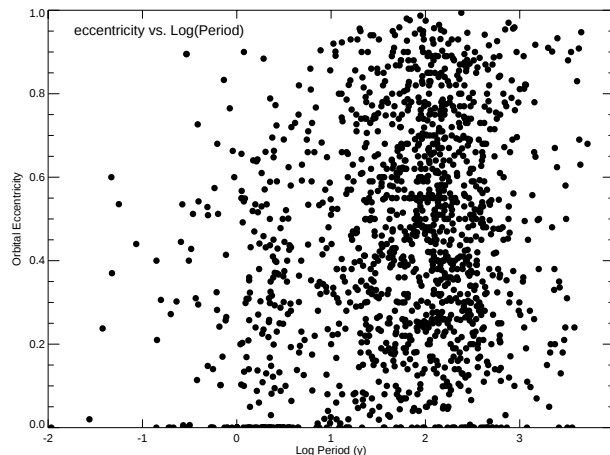


FIG. 8.—Plot of $\log P$ vs. e for all orbits in the Fifth Catalog. Eccentricity is assumed to be zero for many long-period systems; these are typically first orbits and usually of low quality.

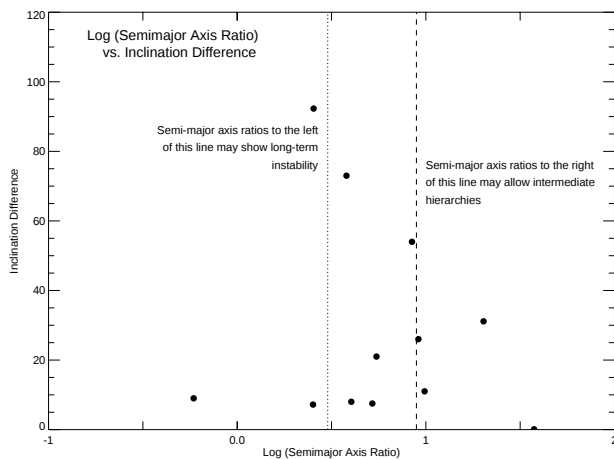


FIG. 9.—Logarithm of semimajor-axis ratio vs. inclination difference for 20 hierarchical systems.

systems for identification of higher order motions or sub-motions is discouraged.

5. CATALOG STATISTICS

Various statistical comparisons of the Fifth Catalog can be made, both with earlier orbit catalogs and with itself. Figures 6 and 7 show the distribution of orbits with grade and period for the current catalog, together with the corresponding numbers for three earlier catalogs.

Figure 8 shows a plot of $\log P$ versus e for the orbits in the Fifth Catalog. The dramatic circularization seen in similar plots for spectroscopic binaries is not seen in resolved binaries, because of their longer periods.

Finally, Figure 9 is a plot of the ratio $\text{periastron}_{\text{outer binary}}/\text{apastron}_{\text{inner binary}}$ versus $|i_{\text{outer binary}} - i_{\text{inner binary}}|$ for the 20 hierarchical systems with visual orbits determined for both hierarchies. Harrington (1992) quantified a value of 3 for the ratio of $\text{periastron}_{\text{outer binary}}$ to $\text{apastron}_{\text{inner binary}}$ as the critical factor for long-term stability (assuming equal-mass companions). Hierarchies to the left of the dotted line may demonstrate long-term instabilities, while those to the right of the dashed line have ratios that may allow intermediate hierarchies.

Systems that are *mildly* interacting may show a tendency toward coplanarity, so the tendency of smaller inclination

differences to have smaller period ratios is not surprising. Five systems lie between the dotted and dashed lines.

02291 + 6724 = CHR 6 Aa + STF 262 Aa-B: Both orbits are of grade 5 and the ratio here is suspect.

06003 – 3102 = HU 1399 AB + HJ 3823 AB-C: This one is the closest to the line, and the incomplete orbital coverage of the wider system may be the culprit.

08592 + 4803 = HU 628 BC + HJ 2477 A-BC: The orbit for the wider system is highly suspect. There seems to be a systematic drift in the $O - C$ values for this orbit, and it may not be even a physical association.

23019 + 4220 = BLA 12 Aa + WRH 37 Aa-B: The short-period orbit is based on only five data points (one of those with a large residual) and needs more data.

23393 + 4543 = CHR 149 Aa + 3A 643 Aa-B: Also suffering from a paucity of data, the short-period system here has only four differential measures.

6. THE USNO DOUBLE STAR CD

A version of the Fifth Catalog current to 2001 January 1 has been included on the 2001 US Naval Observatory Double Star CD-ROM, together with the summary catalog of the Washington Double Star database (Mason et al. 2001), the Third Catalog of Interferometric Measurements of Binary Stars (Hartkopf, McAlister, & Mason 2001b), and the USNO Photometric Magnitude Difference Catalog (Worley, Mason, & Wycoff 2001). The other papers in this series provide descriptions of these catalogs. Both text and HTML versions of the main catalog and the calibration candidate list are included, as are GIF and PostScript versions of all figures. Copies of this CD are available free of charge from the authors.

Thanks foremost to the US Naval Observatory for four decades' worth of support for the authors' double star observing and cataloging efforts. Thanks also to Professor Wulff Heintz and the late William Finsen, without whose efforts this series of catalogs would never have existed. This catalog has made use of the SIMBAD database, operated at CDS, Strasbourg, France. We dedicate this catalog to the memory of Charles Edmund Worley, our colleague and friend.

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