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ORIGINAL ARTICLE

Uncertainties in Ground-Based Visual Double Star Measures

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ABSTRACT

Stellar masses are found from the orbital elements of binary systems which are, in turn, computed from weighted astrometric measures. Astrometric measures of double stars (their position angle and separation) rarely include uncertainties, and published binary star orbits rarely include the weighting systems used in the determination of the orbital elements. Here we propose a simple method for estimating uncertainties of ground-based measures of visual double stars based on precision space-based astrometry of optical (not binary) double stars, which can be used as unbiased weights for all double star measures. The precision of ground-based measures is examined as (i) a function of the date of observation, (ii) the telescope aperture, and (iii) the instrumentation (technique) used at the telescope. We also note in the Appendix, 19 pairs that are incorrectly described in Lin2 and six rectilinear pairs that may display curved motion.

1 | Introduction

The determination of the masses of stars is foundational in stellar astrophysics. An important first step is to apply Keplerian and Newtonian physics to astrometric observations of binary star systems (Serenelli, Weiss, and Aerts 2021).

Gaia DR3 (Gaia Collaboration et al. 2023) and HIPPARCOS (European Space Agency, 1997) space-based astrometric missions have delivered stellar positions of unprecedented precision compared to traditional ground-based optical astrometry. The Position Angle, θ (in degrees), and angular Separation, ρ (in arc-seconds), measures derived from the *All-sky compiled catalogue of 2.5 million stars* (ASCC, Kharchenko 2001, a larger database than HIPPARCOS, where the data is based on and homogenised with HIPPARCOS) and *Gaia DR3* (Gaia Collaboration et al. 2023), are available for pairs for epochs 1991.25 and 2016.0, respectively. The remarkable precision of these space-based measures bolsters the accuracy of derived orbital parameters, subsequently enhancing the precision of star-mass determinations.

However, the determination of the orbits of visual binary systems requires more than two epochs (a minimum of five is required), and the relatively small epoch difference between ASCC and *Gaia DR3* (24.75 years) is too short to contribute strongly to the accuracy of orbital elements for typical periods of decades to tens of thousands of years.

In light of these constraints, the distribution of orbital periods based on well-established data exhibits a peak around 100 years (Malkov and Chulkov 2017). This bias toward shorter periods results in various selection effects in orbit interpretation, as highlighted by Malkov and Chulkov (2017).

Longer period orbits are challenging because of the minimal observed motion over time. Short arcs especially benefit from precision astrometry (Letchford, White, and Brown 2022b).

Ground-based measures are needed to complement high-precision space-based data. The earliest ground-based measures are the most valuable as they define larger portions of the orbit arc. However, the reality is that the precision of measures is improving with time (the consequence of improvements in instrumentation i.e., technique), and thus earlier measures are (assumed to be) of lesser accuracy and, therefore, demand lower numerical weight in orbit computation.

The presence of unknown systematic (bias) and accidental errors (1σ standard deviations or uncertainties) in the orbital elements is due to the precision of the astrometric measurements. Aitken (1918, 1964) advised that the original uncorrected measures of every observer should be used, with the measures weighted for systematic or personal errors derived only after plotting the 'curves' defined by these measures. This guidance results from the general absence of published uncertainties. If, importantly, the uncertainties in the ground-based measures can be reliably estimated directly, they can serve as an objective system of statistical weights.

To date, two primary methods have been employed for estimating bias and uncertainty in visual binary star measures.

The first is estimation of the relative strength of individual measures by experienced workers in the field, based on factors such as telescope aperture, double star separation, magnitude difference and observer expertise (Hartkopf, Mason, and Worley 2001; Hartkopf, McAlister, and Mason 2001; Mason, Douglass, and Hartkopf 1999). This procedure lacks rigor and repeatability, and the uncertainties/weights are typically not published.

The second involves determining the bias of each measure relative to the calculated (ephemeris) position on well-established orbits. This follows Aitken's approach and allows for the estimation of mean bias and uncertainty, both for individual measures and individual observers (Pannunzio, Massone, and Morbidelli 1988; Pannunzio et al. 1986). However, this method is limited by the fact that the well-established orbits from which biases and uncertainties are derived are themselves based on predetermined or nondetermined weights (Douglass and Worley 1992; Hartkopf, McAlister, and Franz 1989). It is to be noted that the *Sixth Catalog of Orbits of Visual Binary Stars* (Matson et al. 2023) grades the orbits according to the weighting scheme in Hartkopf, Mason, and Worley (2001), and the orbits themselves may be the result of the computation and weighting methods in the original publications.

In a previous work (White, Letchford, and Ernest 2018), we used the Aitken method to estimate the accuracy of double star measures decade-by-decade by comparing the *Washington Double Star Catalog* (WDS, Mason et al. 2001) ground-based measures of α Cen AB with the published orbit from the *Sixth Catalog of Orbits of Visual Binary Stars*. The results of this work are discussed below.

2 | Method

We present here a study to assess the precision of ground-based measurements with the objective of estimating the weights for the inclusion of measures in orbit determinations.

This unbiased alternative follows from our paper (Letchford, White, and Brown 2022c), which promotes the determination of rectilinear elements of optical double stars based only on space-based data. Using high-precision astrometry from ASCC and *Gaia DR3* we determined the relative positions of the primary and secondary of confirmed optical pairs at two epochs, 1991.25 and 2016.0. Using these two positions of the secondary relative to the fixed primary, we were able to calculate rectilinear elements at equinox J2000 with uncertainties at least one order of magnitude smaller than other methods. The ground-based telescope measures support, but do not determine, the rectilinear elements.

For this study, we create a pool of *rectilinear* pairs selected from the 2022 August 23 edition of Lin2. That edition of Lin2 contains 1288 sets of rectilinear elements for 1288 pairs of double stars. Approximately 98% of components 1 and 2 (in most cases the primary and secondary) have a *Gaia DR3* source identifier, with fewer having an ASCC identifier.

Of the 1288 doubles in Lin2, 888 had both ASCC and *Gaia DR3* data, allowing rectilinear elements to be calculated based only on the ASCC and *Gaia DR3* measures following the method of Letchford, White, and Brown (2022c). Each double was checked for correct identification and any curvature in the ground-based measures that may indicate binary or other anomalous motion.

Nineteen of the 888 were found to have problems in identification when *Gaia DR3* identifiers were sought. In particular, the component identifiers for 10 doubles needed to be swapped (secondary mistaken for primary), compared to SIMBAD (Wenger et al. 2000), so that the rectilinear motion derived from ASCC and *Gaia DR3* aligned with the ground-based measures. The list of corrections/conversions applied to the Lin2 data set is given in the Appendix.

Six of the 888 exhibited some curvature similar to slow-moving binaries when compared with space-based rectilinear motion (STF 978AB, J 1011, COO 138, DUN 187, WNO 5AB, HJ 4917) and were withdrawn from further computations. Details are in the Appendix, Figures 1–6.

Working only with the 882 above catalogued visual double stars of Lin2 for which ASCC and *Gaia DR3* positions are known for both components, and adopting J2000.0 as our standard epoch for all computations, we compute for each pair a 'proper motion vector' for the secondary relative to its primary, as detailed in Letchford, White, and Brown (2022c).

This ASCC-*Gaia DR3* proper-motion vector is thus defined by the space-based measures and allows the computation of the 'space-based' position angle (θ_C) and separation (ρ_C) measure at any epoch. The letter C here denotes these as computed measures.

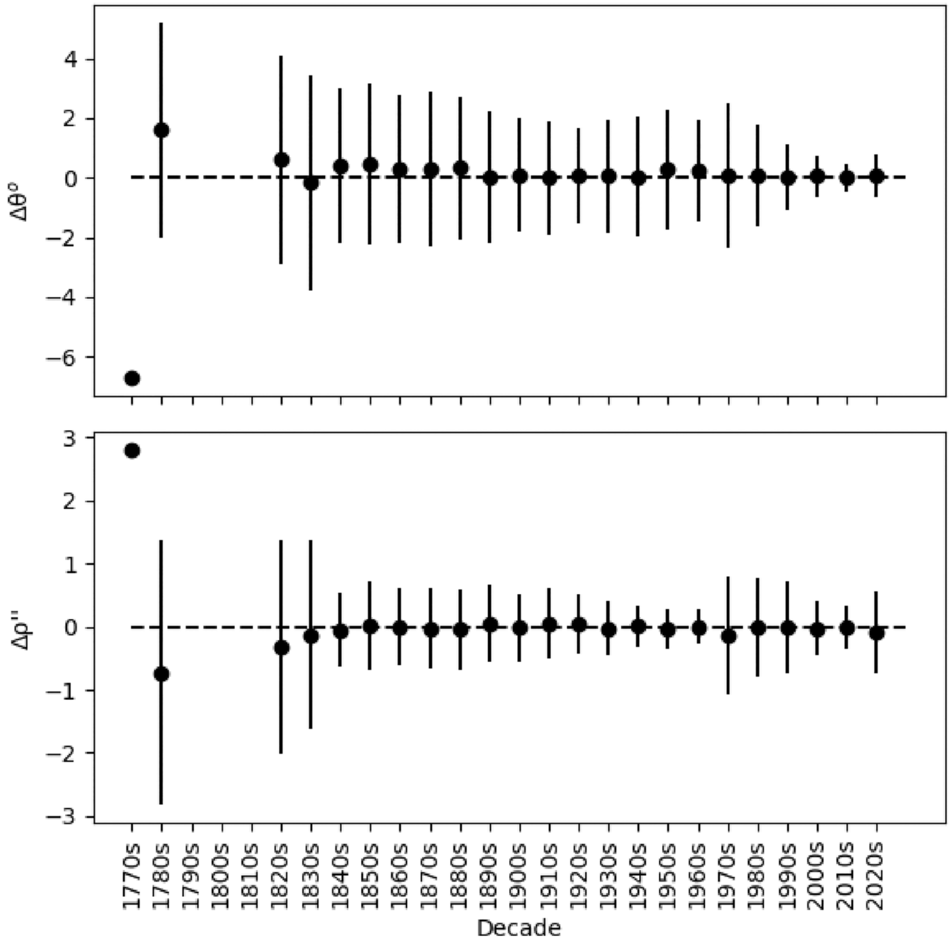


FIGURE 1 | The averaged $\Delta\theta$, and $\Delta\rho$ in decades of observation. The mean value is shown as a dot and the standard deviation ($\sigma\Delta\theta$ and $\sigma\Delta\rho$, respectively) as an error bar. Top panel *y*-axis is $\Delta\theta$ in degrees (°) and the bottom *y*-axis is $\Delta\rho$ in arc-seconds (″). This figure is developed from the data in Table 1.

Defining the ground-based observed measures as O and the computed measures as C, the differences $(O - C)$ at the observation epoch determine the observational uncertainty (σ) in that ground-based measure. Any 180° ambiguities in θ were corrected.

For the 882 pairs and the ground-based measures of these pairs available from the WDS, an initial database of 36,855 rows of data was produced. The observed measures are from 682 observers and were made with various telescopes and measurement instruments (techniques), between 1779.8 and 2022.2.

To clean the data, we deleted from our data base all rows where one or more of the following ground-based data was missing: a measure of θ ('theta'), a measure of ρ ('rho'), indication of measuring technique ('tech'), discoverer code ('DisC'), observer code ('ref'), and telescope aperture ('tel'). The shorthand terms 'theta', 'rho', 'DisC', 'tech', 'ref', and 'tel' are those used in the Lin2.

In addition, we have adopted the philosophy that measures where the $(O - C)$ in ρ is greater than 5 arc-seconds are blunders (reading errors, transcription errors, the results of immature observers, etc.) and these are rejected from the data base of $(O - C)$ values. A small number of $(O - C)$ values as high as hundreds of arc-seconds were found and rejected.

Similarly, we reject data where the $(O - C)$ values of θ are greater than 10° for ρ greater than 10 arc-seconds, and greater than 30° for ρ less than 10 arc-seconds. This limitation is to avoid poor O values in θ and the possibility of otherwise unresolved 180° ambiguities in θ.

Further, to eliminate space-based measures, we deleted all rows with TYC (TYCHO) and HIP (HIPPARCOS) in the'ref' column and H (HIPPARCOS/Tycho, HST, Spitzer, or other space-based techniques) in the 'tech' column. Data from ASCC and *Gaia DR3* were not rejected. Data from non-optical pass bands present in Lin2 were also not rejected.

The above rejections leave 26,205 sets of astrometric measures from 857 pairs by 613 observers from 25 different-sized aperture telescopes using 39 different instruments (techniques). We chose not to further trim the data at the three-sigma level.

Now, we define the differences $(O - C)$ in θ and ρ as $\Delta\theta$ and $\Delta\rho$, and we adopt the mean values of $\Delta\theta$ and $\Delta\rho$ as the bias (μ) in the ground-based measures. In addition, we define $\sigma\Delta\theta$ and $\sigma\Delta\rho$ as one sigma (1σ) standard deviations of the values $\Delta\theta$ and $\Delta\rho$, respectively.

Starting with this refined data set we explore the accuracy of over 200 years of ground-based double star astrometry as a function of:

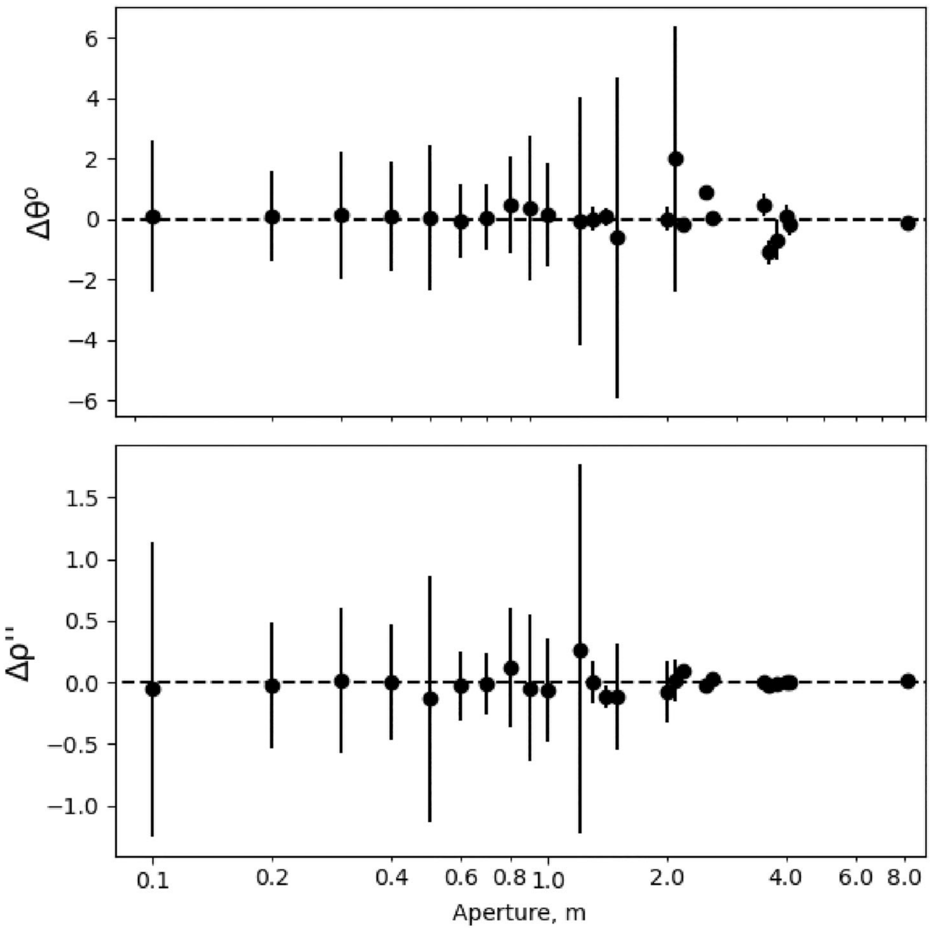


FIGURE 2 | Graphical representation of data in Table 2. The horizontal axis is the aperture of the telescope in meters. The mean value is shown as a dot and the standard deviation as an error bar.

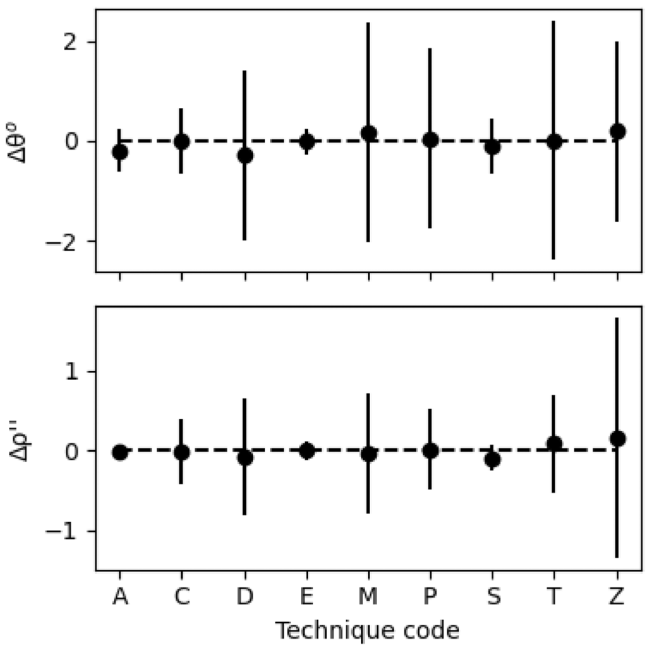


FIGURE 3 | Graphical form of the data in Table 3. The horizontal axis is the technique code. See Section 3.3 for explanation. Again the mean value is shown as a dot and the standard deviation as an error bar.

- The epoch of observation.
- The aperture of the telescope.
- The technique (instrumentation).

2.1 | The Precision of the Computed (C) Ground-Based Measures

The ASCC-*Gaia DR3* proper motion vector is determined from the ASCC and *Gaia DR3* positions, and the ASCC and *Gaia DR3* epochs. The errors published in these space-based databases were propagated to the generated rectilinear elements (see Letchford, White, and Brown 2022c for details). Using these data, a detailed analysis for the 26,205 O estimates for the 857 pairs studied shows the *median* uncertainties in the calculated measures of θ and ρ to be 0.23° and 0.077″ in the 1820s, reducing to a diminishing small 0.0041° and 0.0018″ for the 2010s. These medians are the insignificant uncertainty in the C component of $\Delta\theta$ and $\Delta\rho$.

Forty-one measures made with modern electronic techniques (S—speckle interferometry; St—Tokovinin 'hrcam' and Ao—adaptive optics coronagraph) and telescopes of 4.1 m or larger are available to independently test the accuracy of the C measures. For this sample, the standard deviation in $\Delta\rho$ is $\pm 0.0076''$, implying that, for this data set made with a large

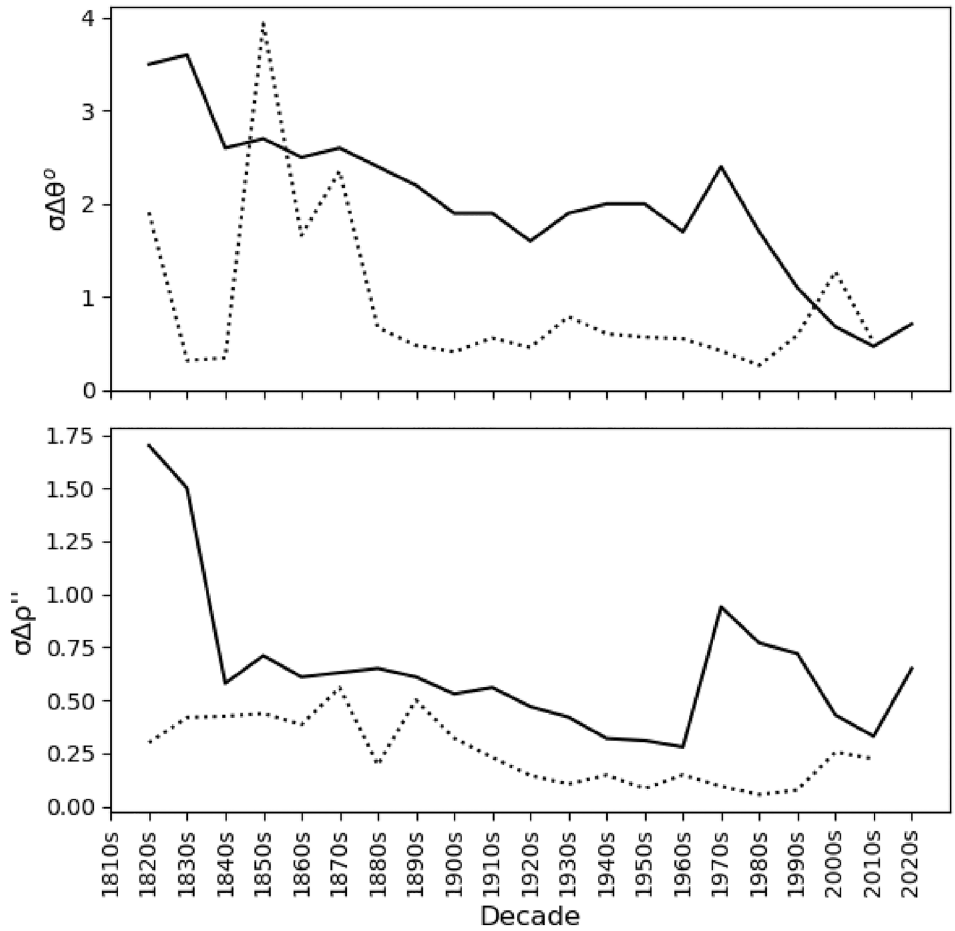


FIGURE 4 | Comparison plots of results obtained from the present research (continuous line) and the results of our earlier paper on α Cen AB (dotted line). See Figure 1 for more detail.

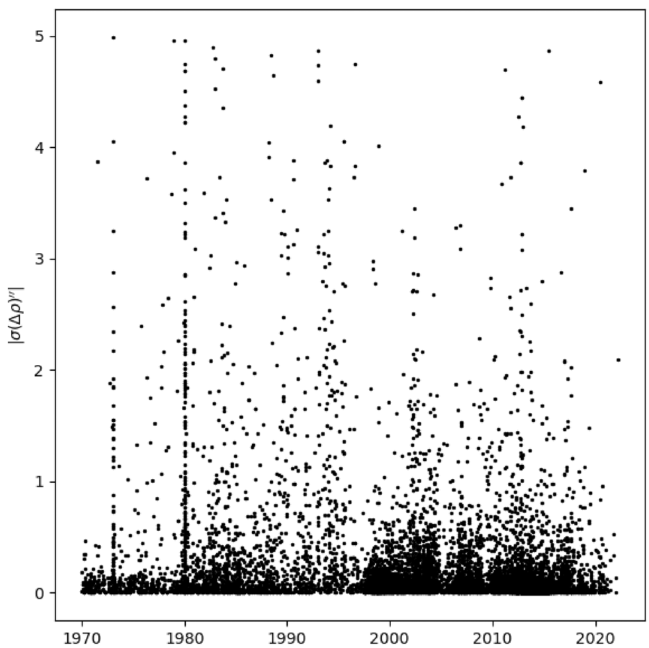


FIGURE 5 | Absolute value of $\Delta\rho$ for the years 1970.0–2022.2 showing verticals where inferior measures have been added to the Lin2 (and hence WDS) data base.

telescope and modern techniques, the values of C are restricted to the milliarcsecond range.

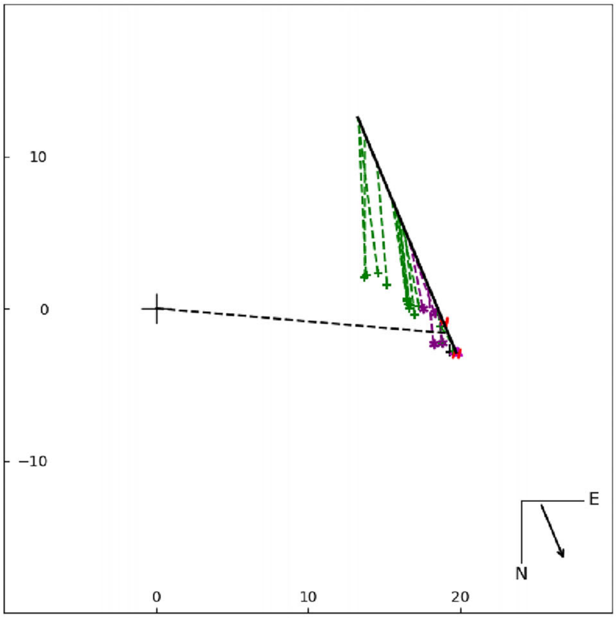
2.2 | This Is Applicable to all Pairs Not Just Visual/Rectilinear Doubles

The measured uncertainties in $\Delta\theta$ and $\Delta\rho$ here are from observations of optical (rectilinear) double stars, not for stars in binary orbits. However, these ground-based measures were made (presumably) without knowledge of any association of the stars and are therefore truly indicative of measures made at similar epochs by the same observer, using the same telescope and technique. Thus, these uncertainty estimates can be used as weights for the computation of orbital elements *etc*., which are free of 'cyclic' determinations and subjective knowledge of the data sets.

3 | Results

3.1 | Epoch of Observation

Table 1 gives the decade, the number of measures recorded in that decade and the uncertainty, σ, in $\Delta\theta$ and $\Delta\rho$ for the 26,205 measures considered for each decade of observation. Units are degrees ($^{\mathrm{o}}$) and arc-seconds ($''$), respectively. The error bars in



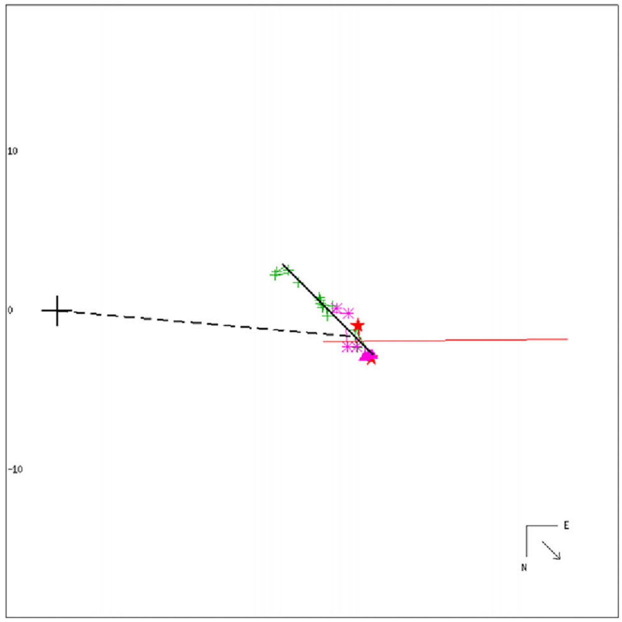


FIGURE 6 | Rectilinear plots of 06555 + 3755 STF 978AB. The left plot uses the method employed here and described fully in Letchford, White, and Brown (2022c). The right plot is from the WDS (Lin2) and uses a weighted least squares fit.

TABLE 1 | Uncertainties, σ, in $\Delta\theta$, and $\Delta\rho$ in decades of observation.

Decade	Number of measures	$\sigma\Delta\theta^o$	$\sigma\Delta\rho''$
1770s	1		
1780s	28	3.6	2.1
1790s			
1800s			
1810s			
1820s	204	3.5	1.7
1830s	391	3.6	1.5
1840s	290	2.6	0.58
1850s	343	2.7	0.71
1860s	547	2.5	0.61
1870s	812	2.6	0.63
1880s	965	2.4	0.65
1890s	1672	2.2	0.61
1900s	2464	1.9	0.53
1910s	2116	1.9	0.56
1920s	1400	1.6	0.47
1930s	841	1.9	0.42
1940s	410	2	0.32
1950s	865	2	0.31
1960s	830	1.7	0.28
1970s	839	2.4	0.94
1980s	1157	1.7	0.77
1990s	1533	1.1	0.72
2000s	2682	0.68	0.43
2010s	5746	0.47	0.33
2020s	69	0.71	0.65

Figure 7 represent $\sigma\Delta\theta$ and $\sigma\Delta\rho$; the plotted point is the mean of $(O - C)$ which is the bias in $(O - C)$.

There is a steady decrease in $\sigma\Delta\theta$ and $\sigma\Delta\rho$ with epoch, with the decrease in the uncertainty of θ measures being less obvious.

The biases in the period 1820s–2020s range from -0.16° to $+0.60^{\circ}$ and $-0.32''$ to $+0.055''$. In the same period, the uncertainties range from $\pm0.47^{\circ}$ to $\pm3.6^{\circ}$ and $\pm 0.28''$ to $\pm1.7''$, for $\Delta\theta$ and $\Delta\rho$, respectively. In almost all cases, the bias is small relative to the standard deviation σ (uncertainty) and is ignored in this and subsequent discussions.

3.2 | Aperture

Available in the Lin2 database is a rounded off record of the size of the telescope used in the ground-based measures. Table 2 presents the uncertainties of $\sigma\Delta\theta$ and $\sigma\Delta\rho$ as a function of the aperture of the telescope, and Figure 8 depicts the data in Table 2 in a graphical form.

3.3 | Technique

Also available in the Lin2 database is the instrument/detector attached to the telescope used for the ground-based measures. These are described as a class ($A, C \dots Z$) below, and subclasses of these. Different instruments or techniques appear at different epochs in history.

The WDS technique codes ('tech') in Table 3 and Figure 9 are abbreviated as follows:

- A = adaptive optics
- C = CCD or other two-dimensional electronic imaging

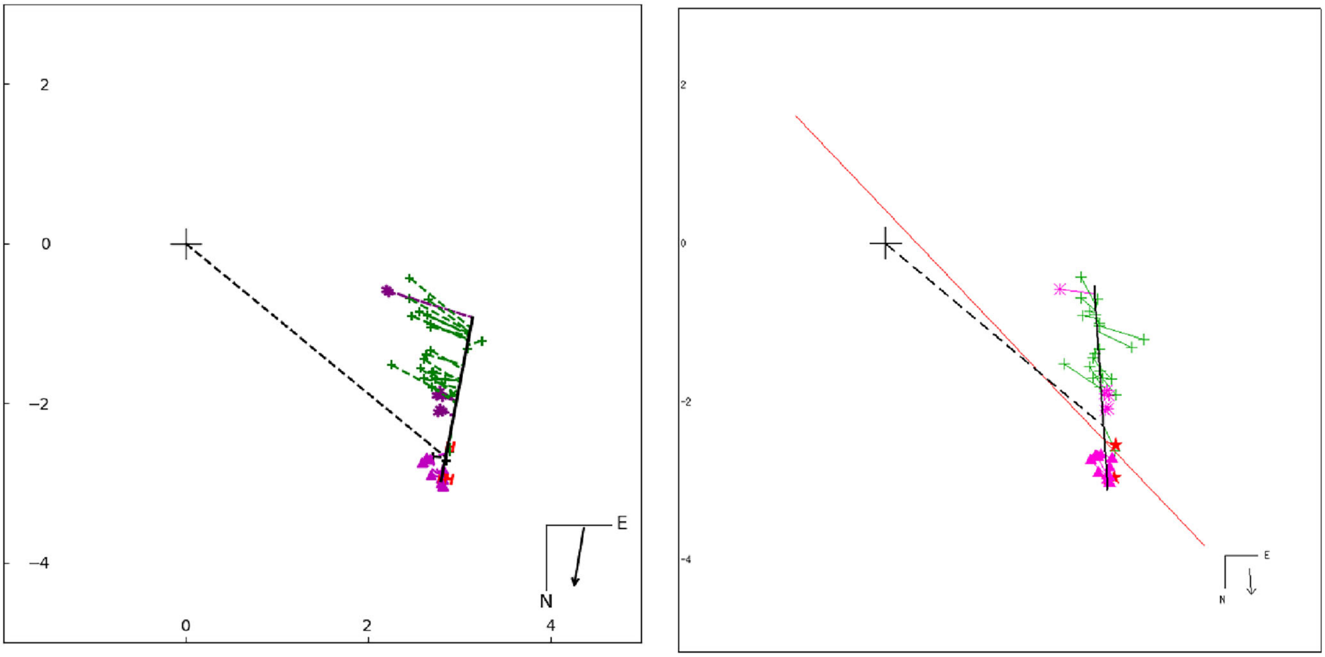


FIGURE 7 | Rectilinear plots of 11,128 + 0453 J 1011. The left plot uses the method employed here and described fully in Letchford, White, and Brown (2022c). The right plot is from the WDS (Lin2) and uses a weighted least squares fit.

TABLE 2 | Table of uncertainties, σ, for $\Delta\theta$ and $\Delta\rho$ for the 25 different sized telescope apertures.

Aperture, m	Number of measures	First epoch	Last epoch	$\sigma\Delta\theta^{o}$	$\sigma\Delta\rho''$
0.1	1295	1783	2020.48	2.5	1.2
0.2	9924	1779.77	2022.219	1.5	0.51
0.3	5174	1824.99	2021.969	2.1	0.59
0.4	1796	1839.83	2020.87	1.8	0.47
0.5	1170	1825	2017.878	2.4	1
0.6	548	1896.67	2022.0465	1.2	0.28
0.7	3603	1840.27	2019.942	1.1	0.25
0.8	169	1884.3	2014.831	1.6	0.48
0.9	327	1888.7	2013.423	2.4	0.6
1	810	1897.82	2016.331	1.7	0.42
1.2	175	1893.292	2005.48	4.1	1.5
1.3	835	1997.44	2010.14	0.41	0.17
1.4	11	2016.5708	2020.6955	0.28	0.091
1.5	23	1926.36	2013.6251	5.3	0.43
2	229	1998.7933	2020.8593	0.42	0.25
2.1	37	1944.24	2011.8539	4.4	0.17
2.2	1	1985.976	1985.976		
2.5	1	2007.8078	2007.8078		
2.6	1	2015.048	2015.048		
3.5	11	1998.9261	2012.103	0.39	0.02
3.6	4	1980.015	2004.9854	0.4	0.02
3.8	17	1975.9556	2010.0652	0.65	0.037
4	3	1989.9375	2006.1908	0.34	0.0053
4.1	37	2008.766	2020.9246	0.38	0.0067
8.1	4	2010.0836	2010.0837	0.085	0.0099

- D = Heliometer
- E = wide-field CCD or other two-dimensional electronic imaging, primarily for large surveys (e.g., 2MASS, SDSS, etc.)
- M = micrometry instrumentation
- P = photographic instrumentation
- S = speckle interferometric instrumentation
- T = Transit circle/Meridian circle
- Z = photometric instrumentation

Table 3 gives the uncertainties found in the data created using these instruments. Figure 9 represents these uncertainties graphically.

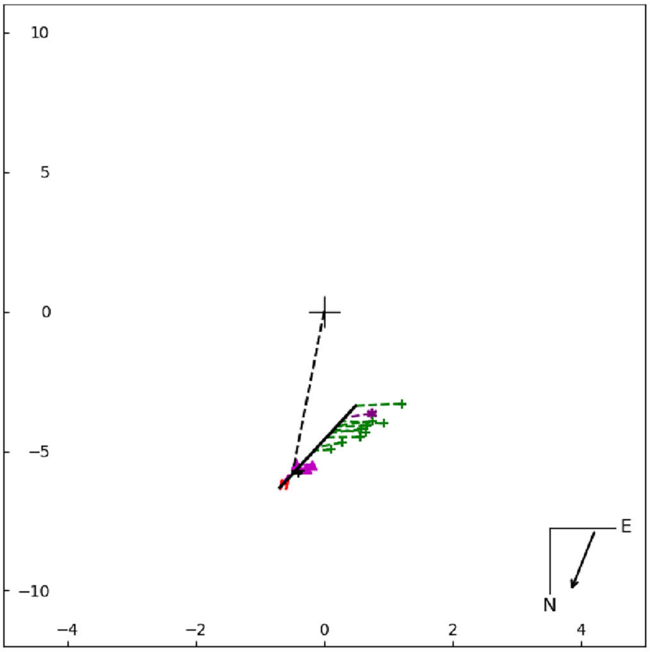
4 | Discussion

4.1 | Epoch of Observation

Table 1 and Figure 7 show a steady improvement in the accuracy of the measures with date.

Several epoch periods are noted. The defining nature of these periods is most likely a combination of the available telescopes, the measurement technique, and changes in the science objectives; such as moving from discovery of new pairs to astrometric re-measurement of known pairs.

Early observations, made around ~1780, and between ~1820 and ~1840, have measured uncertainties of $\pm 4^{o}$ in θ and $\pm 2''$ in ρ.



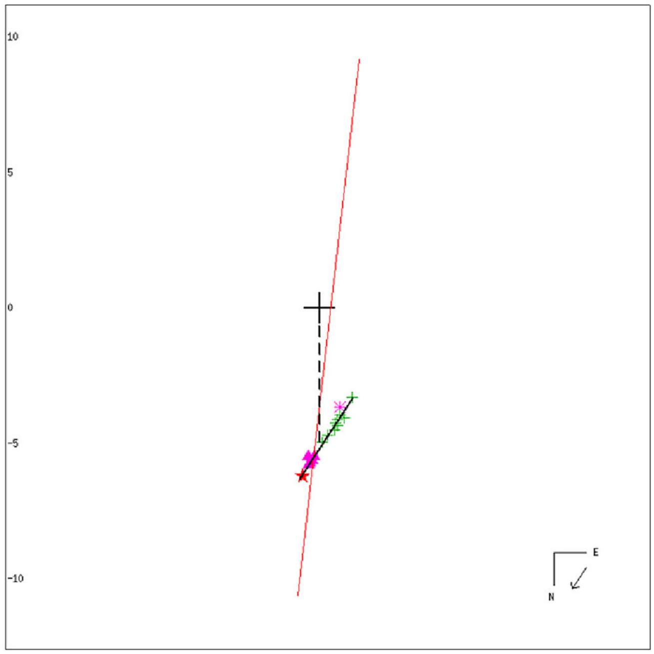


FIGURE 8 | Rectilinear plots of WDS 12272-3408 COO 138. The left plot uses the method employed here and described fully in Letchford, White, and Brown (2022c). The right plot is from the WDS (Lin2) and uses a weighted least squares fit.

TABLE 3 | Uncertainties (σ) for $\Delta\theta$ and $\Delta\rho$ for the 10 principal technique groups. See Section 3.3 for explanation.

Technique	Number of measures	First epoch	Last epoch	$\sigma\Delta\theta^o$	$\sigma\Delta\rho''$
A	13	2003.9724	2015.048	0.43	0.031
C	3219	1952.711	2022.219	0.66	0.41
D	101	1835.25	1895.52	1.7	0.73
E	5202	1983.36	2015.414	0.26	0.12
M	11,773	1779.77	2021.153	2.2	0.75
P	5041	1840.27	2006.66	1.8	0.51
S	327	1975.9556	2022.0465	0.55	0.16
T	510	1850.28	2005.287	2.4	0.61
Z	19	1990.999	1996.846	1.8	1.5

Caution must be exercised when interpreting these early measures. In a previous paper on James Dunlop (Letchford, White, and Brown 2022a), who measured double stars in the southern hemisphere in the 1820s, we found that his uncertainties in θ were $\pm 11^o$ for his 3.25 in. refractor and $\pm 18^o$ for his 9 in. speculum reflector, and his uncertainties in ρ were $\pm 18''$ and $\pm 15''$, respectively. As in the case of Dunlop, we conclude that some measures around the 1820s were made as finding measures rather than with precision for later interpretation.

Between ~1840 and ~1910 the level of accuracy remains constant and from ~1910 to ~1970 there is a steady improvement in accuracy.

Figure 10 displays a comparison between the present results and those of our earlier paper, in which we derived uncertainties based on the current orbital elements of α Cen AB (White, Letchford, and Ernest 2018). Alpha Centauri is the third brightest star and the closest stellar system. Alpha Cen AB is a spectacular binary of first magnitude stars separated by ~2″ to ~22″ with a period of ~80 years. Therefore, α Cen AB has been a prime and easy target and the 449 ground-based measures considered in (White, Letchford, and Ernest 2018) are arguably the best of the art and are superior to the bulk of ground-based measures considered in this paper, as shown in Figure 10.

It is clear from Figure 10 that, generally speaking, our present decadal uncertainties of $\Delta\theta$ and $\Delta\rho$ are larger than those obtained using the published orbital elements of α Cen AB. Although the present results show a steady reduction in uncertainties, those of α Cen AB show a markedly slower decline.

Modern observations after ~1970 show evidence of the inclusion of pairs measured with less than state-of-the-art precision, and some may represent less than professional quality work. The inclusion of these data sets in the WDS is reflected in a decrease in precision in the decade-by-decade analysis (Table 1 and Figure 7).

Figure 11 shows the absolute differences $(O - C)$ in ρ for the period 1970.0–2022.2. This figure illustrates the presence of poorer data, which is seen here as vertical spikes rising above the continuum of quality measures of ~0.45″. In interpreting uncertainties from this period care must be taken to identify the inferior data sets and avoid using averages that are poisoned by the inclusion of these data. Observation data in the WDS (References And Discoverer Codes) may prove invaluable in recognising poorer quality data, and we note that the two dominate peaks in Figure 5, at epoch 1972.999 (59 pairs) and 1979.999/1980 (162 pairs), can be traced to observer code Cll, which results from amateur micrometre measures, Ma, from a 0.1 *m* telescope. Other peaks are harder

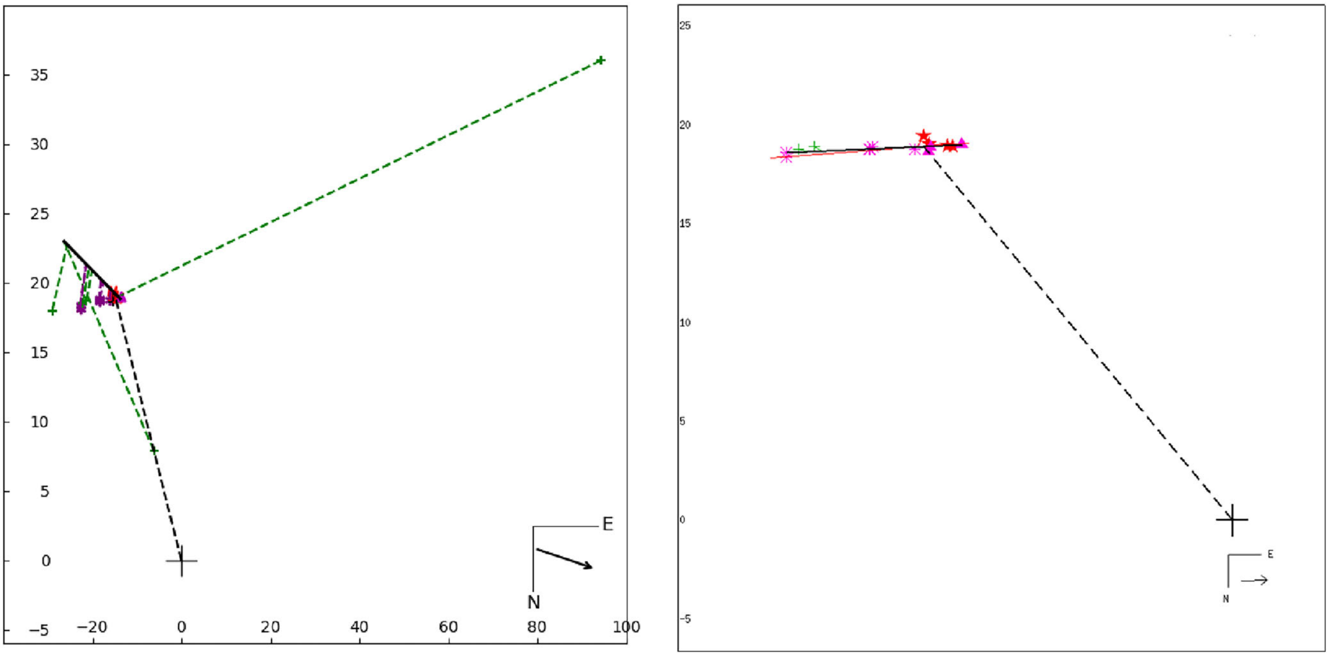


FIGURE 9 | Rectilinear plots of WDS 15336-4732 DUN 187. The left plot uses the method employed here and described fully in Letchford, White, and Brown (2022c). The right plot is from the WDS (Lin2) and uses a weighted least squares fit.

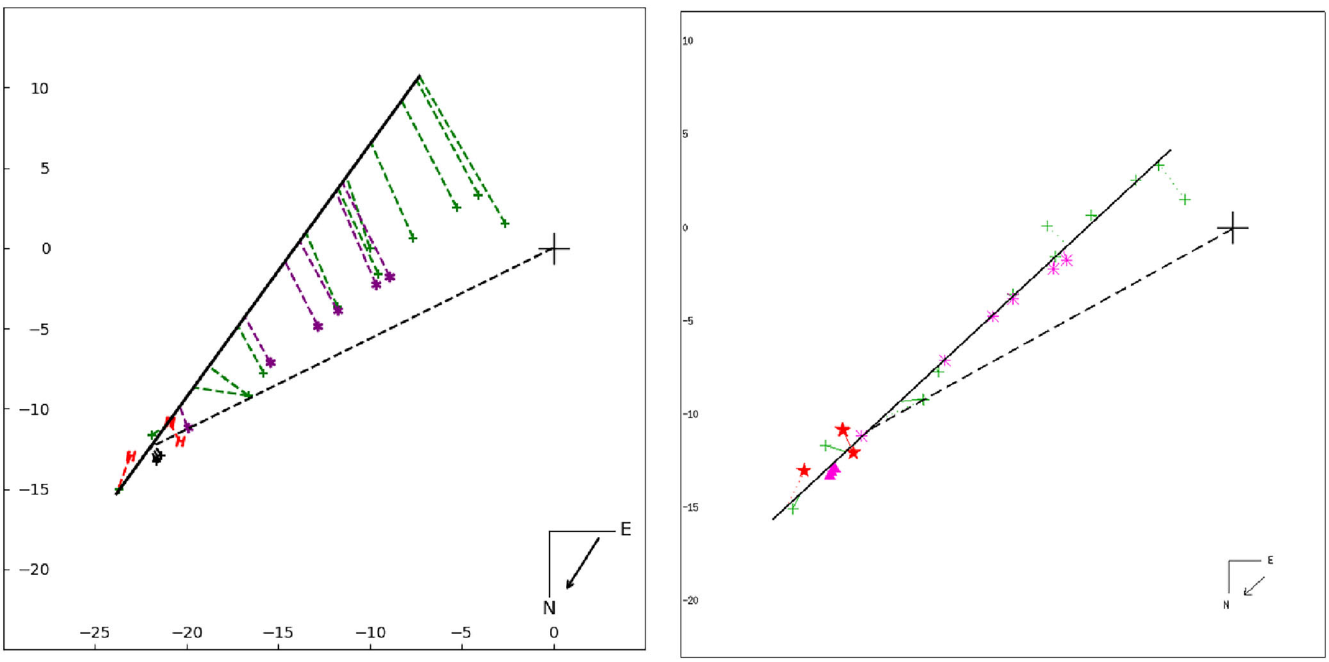
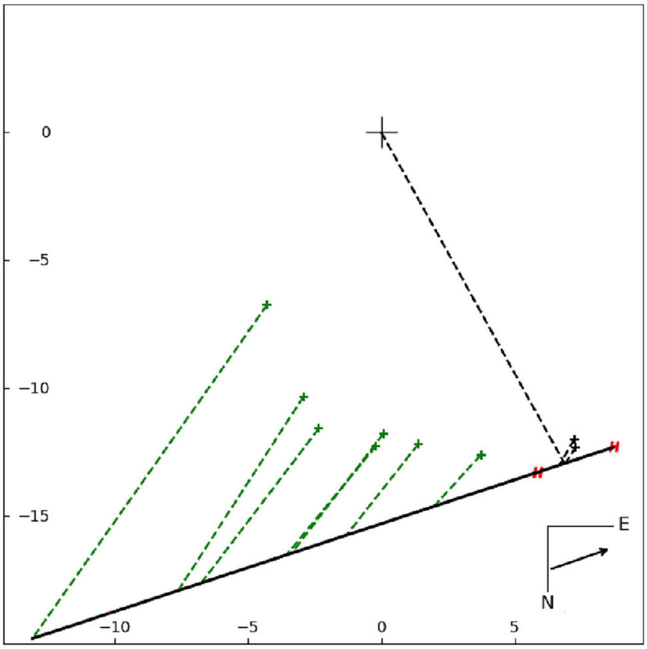


FIGURE 10 | Rectilinear plots of WDS 17054-3346 WNO 5AB. The left plot uses the method employed here and described fully in Letchford, White, and Brown (2022c). The right plot is from the WDS (Lin2) and uses a weighted least squares fit.

to reconcile, but a statistical cut based on the median through this period will tighten the data set.

4.2 | Aperture

Perhaps somewhat unexpected, for small telescopes (less than 1 m) the accuracy of double star astrometry does not appear to be highly dependent on the aperture of the telescope, as shown in Table 2 and Figure 8. Contrary to expectations, the values $\sigma\Delta\theta$ and $\sigma\Delta\rho$ do not improve with increasing aperture as predicted by the Dawes limit. It is only for telescopes greater than 1 m that is equipped with instrumentation (techniques) that reduces/eliminates atmosphere seeing (such as adaptive optics, speckle interferometry and lucky imaging) that significant improvements in precision are seen.



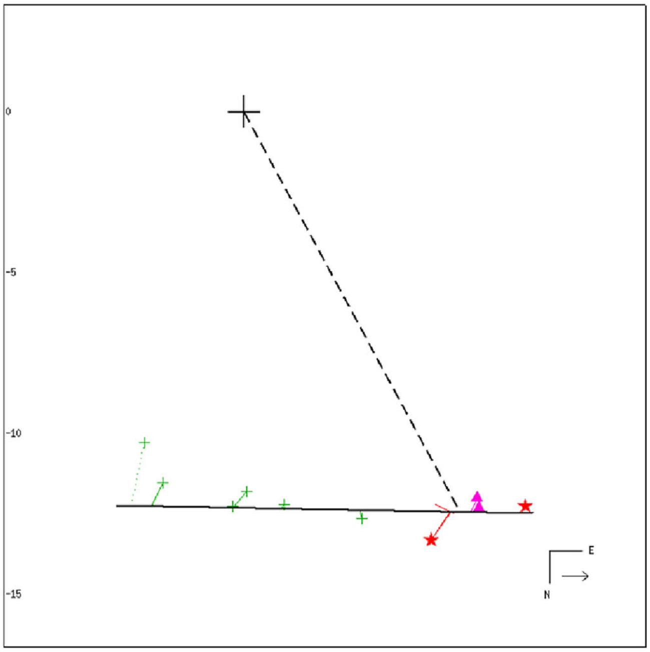


FIGURE 11 | Rectilinear plots of WDS 17097-5420 HJ 4917. The left plot uses the method employed here and described fully in Letchford, White, and Brown (2022c). The right plot is from the WDS (Lin2) and uses a weighted least squares fit.

4.3 | Technique

For ground-based observations, the Earth's atmosphere is a limiting/dominating factor, and techniques such as adaptive optics, speckle interferometry and lucky imaging have, to some extent, eased the limitation of ground-based seeing.

The data in Table 3 and Figure 3 shows the $\sigma\Delta\theta$ and $\sigma\Delta\rho$ obtained with each of the categories of techniques adopted. This Table and Figure clearly state that technique S (speckle interferometry), E (wide-field CCD or other two-dimensional electronic imaging) and A (adaptive optics) are superior to other techniques. These are 'modern' techniques first introduced in 1976, 1983, and 2004, respectively. The micrometer, M, is the most widely used technique and has been employed over the period of recorded double star observations. Unfortunately, its accuracy does not compete with modern electronic-based techniques.

5 | Conclusion

The science driving this paper is to establish a method that allows subjective-free estimations of the accuracy of ground-based double star measures, which can then be used for the weighting of measures used in the calculation of binary star orbits (and for the rectilinear elements of visual pairs).

We report above (Sections 3 and 4) trends and analysis of the precision of these measures in relation to date of epoch, telescope size (aperture), and the technique used for the observations.

This work has resulted from a comparison of ground-based measures with space-based measures for catalogued visual optical pairs. This analysis is also applicable to ground-based measures of binary systems, as all measures were made without knowing the nature of the pair. The same observers, telescopes, and techniques were used for binary and non-binary pairs.

Weights are usually applied to measures before the calculation of orbital elements (or rectilinear elements) as the inverse square of the observed uncertainty. Here, we suggest that the uncertainty for any ground-based measure should be estimated using the following.

For observations of a known epoch, estimates of $\sigma\Delta\theta$ and $\sigma\Delta\rho$ can be estimated from Figure 7 and Table 1.

Estimates of uncertainty that depend on the aperture of the telescope and the measurement technique can be obtained from Figures 8 and 9 and Tables 2 and 3.

Estimates of uncertainty obtained in this way may not be totally independent of each other, so caution is suggested when reconciling different estimates.

Finally, we are aware that this work opens up a number of avenues for further analysis of the data, for example, correlations between the size (aperture) of the telescope and date of observation, and indeed a comparison of the uncertainties of individual observers. Such analyses and discussions are in preparation.

5.1 | Caveat

The uncertainties listed in Tables 1–3, have been constructed from a modestly edited set of ground-based measures (see Section 2). Here, approximately 10% of the original set of $\Delta(O-C)$ estimates was rejected under our assumption that serious observers would not publish measures outside of the criteria set out in Section 2. Our caveat, therefore, is that the uncertainties presented here are not applicable to measures that would be rejected.

Similarly, we draw attention to the possible presence of inferior data for measures made later than 1970. The uncertainty for the inferior data will be underestimated, and the uncertainty for the 'good' data in this period may be slightly higher than our Tables present.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Appendix A

Correction/Conversions Made to the Lin2 Data

The description of 19 pairs in the Lin2 was found to be incorrect. In particular, the component identifiers for 10 doubles needed to be swapped (secondary mistaken for primary) so that the rectilinear motion derived from ASCC and *Gaia DR3* aligned with the ground-based measures.

See Table 4 for corrections / conversions made to the Lin2 data.

Rectilinear Pairs That Display Curved Motion

As discussed in Section 2, our analysis of the Lin2 catalogue has revealed that six of the 888 exhibited some curvature similar to slow-moving binaries. These are STF 978AB, J 1011, COO 138, DUN 187, WNO 5AB and HJ 4917. The plots on the left are those according to the method of Letchford, White, and Brown (2022c). The right plot is the Lin2 plot.

TABLE 4 | Table of Lin2 doubles alterations required for this work—see text.

WDS	DisC	Problem
14,165 + 0145	H N 1 AC	B is C
15,565 + 1540	STT 584AB	B is C
10,365 − 1214	KUI 51 AC	B seems to be C
18,032 + 2522	STF2268AC	C is B
15,597 − 6640	HJ 4819CD	CD is AB
12,350 − 4717	HJ 4530A, BC	Component 2 is B
08071 + 6203	STI 662	Component B appears in SIMBAD to be Galaxy MCG+10-12-073
01395 + 3216	SEI 19	IDs swapped A to B
03212 + 0523	BAL2995	IDs swapped A to B
04385 + 2656	STF 572AB	IDs swapped A to B
05047 − 0925	GAL 375	IDs swapped A to B
05418 + 1933	STF 771AB	IDs swapped A to B
09548 − 5205	HJ 4266	IDs swapped A to B
10,140 + 2449	HJ 477AB	IDs swapped A to B
18,326 + 1019	BRT1303	IDs swapped A to B
21,385 + 2323	POU5445	IDs swapped A to B
19,034 + 2603	STF2444	should be 19,038 + 2602 BU 52AB
18,176 + 0333	BAL2487AB	IDs swapped A to B
22,280 + 5742	FYM 118AS	S appears to be H

Note: Columns 1 and 2 remain unchanged. Measures for STT 584AB, KUI 51 AC, HJ 4530A,BC, STI 662, BRT1303, STF2444 and FYM 118AS, were rejected. See Section 2 for rejection criteria.