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Assessment of the accuracy of measures in the 1829 southern double star catalogue of James Dunlop

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ABSTRACT

In 1829 James Dunlop published the first southern double star catalogue of some 253 double stars. The accuracy of this catalogue has been determined by using *Aladin* to cross-match them with *Gaia DR2* and estimate their positional (right ascension, declination, position angle, and separation) and magnitude accuracy. Seven per cent could not be identified using *Aladin* and 14 were single stars. We found 13 double stars (5 per cent) not currently listed in the *Washington Double Star Catalog*. The catalogue equinox was determined as B1826.0. Overall, 1σ uncertainties in right ascension were within 1 sidereal minute and declinations within 10 arcmin. We also identified and corrected a number of Quadrant errors in the position angles and quantified the separations. Apparent visual magnitude estimates were generally within 1 mag. Dunlop's overall uncertainties were larger than those of his contemporaries, nevertheless the little known catalogue remains valuable as the earliest source of over 200 double star astrometric and visual magnitude estimates.

Key words: history and philosophy of astronomy – methods: analytical – astrometry – binaries: visual.

1 INTRODUCTION

Astrometric positions are the core of many astrophysical studies, and historic data often holds the key to accurately determined astrophysical parameters when incorporated with such space missions as *HIPPARCOS* and *Gaia*.

Astrometric and magnitude measures in old double star catalogues are rarely accompanied by estimates of their uncertainties. For double star studies, accurate historic positions lead to firmer distinctions between rectilinear and orbital motion, as in distinguishing binary double stars from optical double stars. Estimates of the multiplicity ratios of stellar systems, for each spectral type, and galactic environment have important ramifications for many aspects of astrophysics especially stellar formation and evolutionary models (Chanamé 2007; Guinan, Harmanec & Hartkopf 2007; Duchêne & Kraus 2013; Andrews, Chanamé & Agüeros 2017; Igoshev & Perets 2019; Moe 2019). An understanding of historic positional uncertainties can lead to tighter estimates of the orbital parameters of binary systems thus contributing to better estimates of fundamental stellar parameters such as mass.

The aims of this paper are to draw attention to and describe; as well as correct and quantify; the first published catalogue of southern double stars, by James Dunlop (Dunlop 1829) titled, *The Approximate Places of 253 Double and Triple Stars for the beginning of 1827, as observed with a 9-feet Reflecting Telescope at Paramatta, New South Wales, from the latter end of 1825 to the beginning of 1827. The Observations were made about* 2^s *of sidereal time east of the Brisbane Observatory*. This paper is referred to here as the *Dunlop Catalogue*. The observations that contributed to it were, in part, carried out at the Parramatta Observatory. The Parramatta Observatory is well represented in the literature (e.g. Richardson & Brisbane 1835; Service 1890; Wood 1966; Bhathal & White 1991; Haynes et al. 1996; Cozens & White 2001; Saunders 2004; Rutledge 2009; Cozens, Walsh & Orchiston 2010; Schaffer 2010; Bickford 2011; Bhathal 2012), where its main goal was to produce a *single* star catalogue of the southern sky which was published in 1835 (Richardson & Brisbane 1835) and is known as the *Brisbane Catalogue*.

The *Dunlop Catalogue* was initially greeted with enthusiasm. Sir John Herschel called the catalogue 'copious and valuable' (Herschel 1828). Some years later, when he conducted his own survey of the southern sky, at the Cape of Good Hope he reversed his praise and claimed that the *Dunlop Catalogue* contained a 'great many mistakes... in the places, descriptions, or measures' (Herschel 1847).

That one comment alone meant that the *Dunlop Catalogue* was practically forgotten after 1847. It is hoped that this paper will also to some degree, restore the reputation of Dunlop and his pioneering double star work.

The first two authors of this paper have previously published material on the *Dunlop Catalogue* (Letchford, White & Ernest 2019a,b,c,d). This present paper represents a more thorough investigation of the astrometric and magnitude estimates of the *Dunlop Catalogue*. Section 2 describes the *Dunlop Catalogue* and the telescopes used. Section 3 will go on to explain the methods used to: quantify its internal consistency; identify the primary and secondary components; calculate the catalogue equinox; estimate the accuracy of the positions, position angles, separations and magnitude estimates; and discusses possible complications and solutions to the methods. The results will be presented and discussed in Section 4, along with recommendations for the observer and a note on the typographical errors in the *Dunlop Catalogue*. Finally in Section 5,

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Table 1. Statistics on entries per column in the *Dunlop Catalogue*. The numbers in brackets indicate statistics for secondary and tertiary components, respectively.

Col.	Column name	*Banks Refractor*	*Dunlop Reflector*
1	No.	119	134
2	Name of Star	119	134
3	Approximate AR	119	134
4	Declination	119	133
5	Angle of Pos	98	73
6	Quadrant	112	101 (3)
7	Distance	60 (3)	77 (2)
8	Δ AR	68	13
9	Δ Declin.	88	16
10	Magnitudes	118 (118) (1)	131 (125) (9)
11	Remarks	33	46

Table 2. Combination of columns from the *Dunlop Catalogue* that can be used to determine Dunlop's *Mean PA* and *Mean Sep*, respectively. Columns 2 and 3 indicate the number of double stars from each telescope for which a position angle and separation could be determined via each method.

Method	*Position angle*	*Banks Refractor*	*Dunlop Reflector*
i	5, 6	97	80
ii	4, 6, 8, 9	63	6
iii	4, 6, 7, 8	22	0
iv	4, 6, 7, 9	35	0
Method	***Separation***	***Banks Refractor***	***Dunlop Reflector***
i	7	60	77
ii	4, 8, 9	67	8
iii	4, 5, 8	55	3
iv	5, 9	70	4

we present some general conclusions. A data file accompanies this paper which digitises the *Dunlop Catalogue*, gives modern identifications, and data generated as a result of our research.

2 DESCRIPTION OF THE *DUNLOP CATALOGUE*

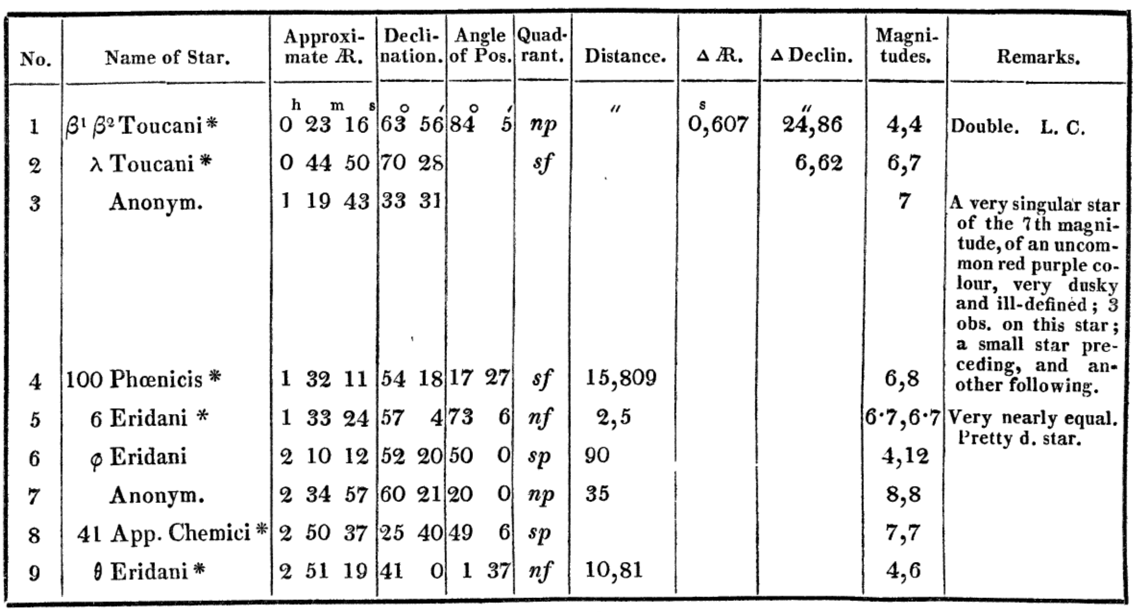
For his observations of double stars (all south of declination −23°), Dunlop used two telescopes herewith referred to as the *Dunlop Reflector* and the *Banks Refractor*. The *Dunlop Reflector* was the main telescope used for his double star work (and his survey of southern non-stellar objects) and was a 9 inch (23 cm) aperture, 9 foot (274 cm) focal length Newtonian with a speculum mirror that Dunlop himself made (Dunlop 1828, 1829). The other telescope, the *Banks Refractor*, was a 3.25 inch (8.3 cm) aperture, 46 inch (117 cm) focal length equatorial-mounted refractor made by Banks of London, equipped with micrometers and setting circles in both hour angle and declination (Dunlop 1829; Lomb 2004; Barker 2008).

The published *Dunlop Catalogue* presents various measures of 253 double stars divided into 11 columns. Statistics on what is presented in each column are given in Table 1 where the numbers in brackets indicate statistics for secondary and tertiary components, respectively. The declination for No. 50 is missing. As can be seen from Table 1, not every double star has a complete set of measures. Measures from the *Banks Refractor* are more complete than those from the *Dunlop Reflector*.

An image of the first nine entries in the original *Dunlop Catalogue* is presented in Fig. 1. A brief description of each column is given here.

Column 1: **No.** Number of the double, 1–253. In the *Washington Double Star Catalog* (WDS, Mason et al. 2001, the central depository for all published double star measures), the discoverer code DUN followed by a number from this column is used to designate the corresponding double from the *Dunlop Catalogue*, however, in the WDS, only 168 of the 253 double stars have DUN as the discoverer code (see Section 4.2).

Column 2: **Name of Star.** One of either a Bayer-style or Flamsteed-style designation (Ashbrook 1984) or 'Anonym.', as in 'Anonymous'. After each of 119 names an asterisk (∗) is placed to indicate that the *Banks Refractor* was used for these measures. The lack of an asterisk indicates that the 9 inch *Dunlop Reflector* was used. We continue to use the asterisk to mark measures from the 3.25 inch *Banks Refractor*.



No.	Name of Star.	Approximate Æ.	Declination.	Angle of Pos.	Quadrant.	Distance.	Δ Æ.	Δ Declin.	Magnitudes.	Remarks.
		h m s	° ′	° ′		″	s	″		
1	β¹ β² Toucani *	0 23 16	63 56	84 5	*np*		0,607	24,86	4,4	Double. L. C.
2	λ Toucani *	0 44 50	70 28		*sf*			6,62	6,7	
3	Anonym.	1 19 43	33 31						7	A very singular star of the 7th magnitude, of an uncommon red purple colour, very dusky and ill-defined; 3 obs. on this star; a small star preceding, and another following.
4	100 Phœnicis *	1 32 11	54 18	17 27	*sf*	15,809			6,8	
5	6 Eridani *	1 33 24	57 4	73 6	*nf*	2,5			6·7,6·7	Very nearly equal. Pretty d. star.
6	φ Eridani	2 10 12	52 20	50 0	*sp*	90			4,12	
7	Anonym.	2 34 57	60 21	20 0	*np*	35			8,8	
8	41 App. Chemici *	2 50 37	25 40	49 6	*sp*				7,7	
9	θ Eridani *	2 51 19	41 0	1 37	*nf*	10,81			4,6	

Figure 1. An image of the first nine entries in the original *Dunlop Catalogue* (Dunlop 1829).

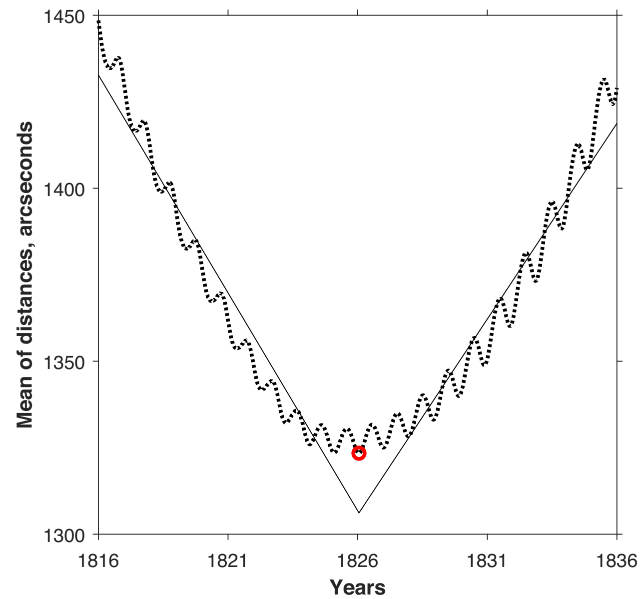


Figure 2. Determination of *Dunlop Catalogue* equinox. The x-axis is the possible Equinox Julian year, the *y*-axis is the mean distance between Dunlop primary positions and *Gaia DR2* precessed primary positions, in acrseconds. The straight lines represent the effect of precession and the dotted oscillating line represents the effect of nutation. The red circle indicates the position of the lowest net separation, at Julian year 1826.05. We adopt 1826.0 as the equinox and epoch of the *Dunlop Catalogue*.

Table 3. Internal consistency of columns 5, 7, 8, and 9 for the *Banks Refractor* in the *Dunlop Catalogue*, illustrated by their Gaussian bias and 1σ values. Linear fits and associated R^2 are from published values versus calculated 'mean' values, again without any outliers removed, and are given to indicate the correlation between them.

Banks Refractor	***Angle of Pos* (column 5)**	***Distance* (column 7)**
1st Gaussian bias	$+51' \pm 47'$	$+1.8'' \pm 1.2''$
1st Gaussian 1σ uncertainty	$377' \pm 34'$	$7.1'' \pm 0.9''$
1st outliers	34∗	34∗
1st OLS slope	+1.04 ± 0.03	+1.12 ± 0.03
1st OLS R^2	0.94	0.98
Banks Refractor	**Δ *AR* (column 8)**	**Δ *Declin* (column 9)**
1st Gaussian bias	$-0.22^{s} \pm 0^{s}.11$	$-1.2'' \pm 0.7''$
1st Gaussian 1σ uncertainty	$0.78^{s} \pm 0^{s}.08$	$5.9'' \pm 0.5''$
1st outliers	78∗, 178∗	242∗
1st OLS slope	+0.96 ± 0.03	+0.96 ± 0.03
1st OLS R^2	0.94	0.96

Column 3: **Approximate AR.** Right ascension of the primary in hours, minutes and whole seconds at the Catalogue equinox and epoch of observation (Section 4.3). The double stars are listed in order of increasing right ascension.

Column 4: **Declination.** Declination of the primary in degrees and whole minutes at the Catalogue equinox and epoch of observation (Section 4.3), measured south from the equator.

Column 5: **Angle of Pos.** The angle of the secondary relative to the primary measured from the parallel of declination of the primary into one of the Quadrants (column 6), in degrees and whole minutes. This is not the same as the present-day position angle (PA) which is the angle of the secondary with respect to the primary measured from the meridian passing through the primary, eastwards from north, in decimal degrees.

Column 6: **Quadrant.** Quadrant of the secondary relative to the primary (n = north, s = south, p = preceeding, and f = following). Thus, position angles between 0° and 90° are in Quadrant nf, between 90° and 180° in sf, between 180° and 270° in sp and between 270° and 360° in np. For Nos. 108, 194, and 211, two Quadrants are given since Dunlop recorded them as triple stars. For some double stars (all from the *Dunlop Reflector*), the Quadrant is given simply by one of the four letters, indicating a PA of either 0° (n), 90° (f), 180° (s), or 270° (p).

Column 7: **Distance.** Angular distance of the secondary from the primary, in arcseconds. Equivalent to separation (Sep).

Column 8: **Δ*AR*.** Absolute difference in right ascension between the primary and secondary, in (sidereal) seconds of right ascension.

Column 9: Δ*Declin.* Absolute difference in declination between the primary and secondary, in arcseconds.

Column 10: **Magnitudes.** Apparent visual *eyeball* magnitude estimates of the primary and secondary. The *Dunlop Catalogue* used an old form of magnitude notation where the point is read as between two magnitudes. When this occurs, we read this being the first magnitude plus 0.5.

Column 11: **Remarks.** Dunlop's notes on selected double stars, e.g. his remark 'Double L. C.' occurs 15 times for the 3.25 inch and 5 times for the 9 inch. This references these double stars to Nicolas-Louis de Lacaille's 1763 catalogue (Lacaille 1763).

Table 4. Identification statistics. 'DUN in WDS' refers to double stars that are present in the *Washington Double Star Catalog* with DUN (for Dunlop) as the discoverer designation. 'Other in WDS' refers to double stars in the WDS with discoverer designations other than DUN. 'unidentified' refers to double stars in the *Dunlop Catalogue* that could not be identified. 'one' indicates that only one star was found to be associated with the Dunlop position. 'Two' indicates that a double star was found but is not currently listed in the WDS. Three, four, five indicates that a three, four, or five star system, respectively, was found at the location in the *Dunlop Catalogue*.

Identification	***Banks Refractor***	***Dunlop Reflector***	**Total**	**Percentage (of 253)**
DUN in WDS	84	84	168	66.4 %
Other in WDS	21	14	35	13.8 %
Unidentified	4	14	18	7.1 %
One	3	11	14	5.5 %
Two	7	3	10	4.0 %
Three	0	5	5	2.0 %
Four	0	2	2	0.8 %
Five	0	1	1	0.4 %

3 METHODS

3.1 Internal consistency

Dunlop did not record the relative position of the secondary in the now familiar position angle and separation measures. Rather, columns 5–9 of the *Dunlop Catalogue* contain data such that the position angle and separation can each be calculated in up to four different ways (see Table 2). Because of this, we define Dunlop's position angle and separation for each double star as the *mean* of the results of each method (*Mean PA* and *Mean Sep*, respectively). Standard trigonometric equations were used to calculate the *Mean PA* and *Mean Sep*, and are given in Appendix B. Any effects the

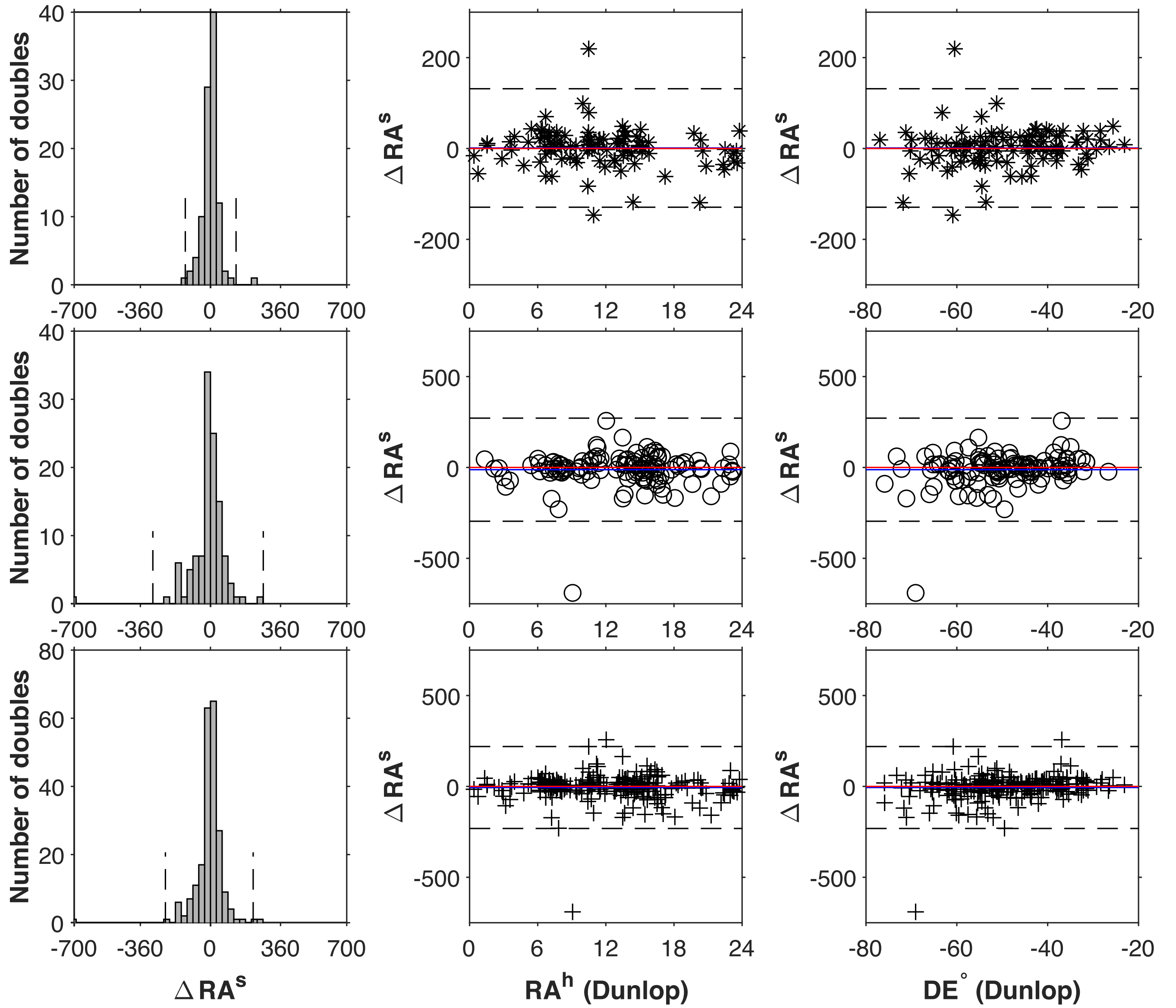


Figure 3. Accuracy of Dunlop's RA in sidereal seconds, without outliers removed. ΔRA^s = Difference in right ascension in sidereal seconds in the sense of equation (1). Note the relatively few but large outliers. Most are probably due to typographical errors in the published catalogue (see Section 4.4). *Left column*: Histograms of number of double stars in the *Dunlop Catalogue* versus ΔRA^s. Bin widths, 30^s in each case, were chosen for plot clarity. The dashed black lines show the Gaussian $\pm 3\sigma$ positions, without outliers removed. *Middle* and *right columns*: Display the following overlays: a solid red line to indicate the unity line; a blue solid line to indicate the Gaussian bias; and dashed black lines to indicate the positions of the Gaussian $\pm 3\sigma$. *Top row*: Distribution of the differences in right ascension (ΔRA^s) for the *Banks Refractor*. *Middle row*: Distribution of the differences in right ascension (ΔRA^s) for the *Dunlop Reflector*. *Bottom row*: Distribution of the differences in right ascension (ΔRA^s) for the for the catalogue as a whole. *Middle column*: Dependence of the differences in right ascension (ΔRA^s) with right ascension (RA^h). *Right column*: Dependence of the differences in right ascension (ΔRA^s) with declination (DE°).

different ways (or lack of) might have on the *Mean PA* and *Mean Sep* are discussed in in Section 4.1.

Internal consistency of columns 5–9 can be estimated by using the *Mean PA* and *Mean Sep* to calculate a 'mean' *Angle of Pos* (column 5), 'mean' *Distance* (column 7), 'mean' ΔAR, and 'mean' $\Delta Declin$ for each double star. The difference between the published values (O) and the 'mean' values (C), in the sense O–C, should give a measure of consistency, by calculating the single peak Gaussian bias and 1σ uncertainties of O–C results, without any outliers removed. The bias and uncertainty of one column was not taken into account when determining the bias and uncertainty of another column. We also calculated the ordinary least-squares linear slope and R^2 of O versus C as a measure of the correlation between the two values.

3.2 Modern identification

A total of 168 double stars from the *Dunlop Catalogue* (84 each from the *Banks Refractor* and *Dunlop Reflector* already have DUN (for Dunlop) as the discoverer code in the WDS. We decided to accept these identifications. To confirm the identity of the remaining double stars in the *Dunlop Catalogue*, the position of each primary was forward precessed to equinox J2000.0. The low precision International Astronomical Union 1976 method (gives < 1 arcsec uncertainty over the required period, Lieske et al. 1977) was used as this does not depend on knowing either parallax or proper motion, and only requires the initial equinox and epoch. Because we began not knowing the catalogue equinox, we assumed an initial

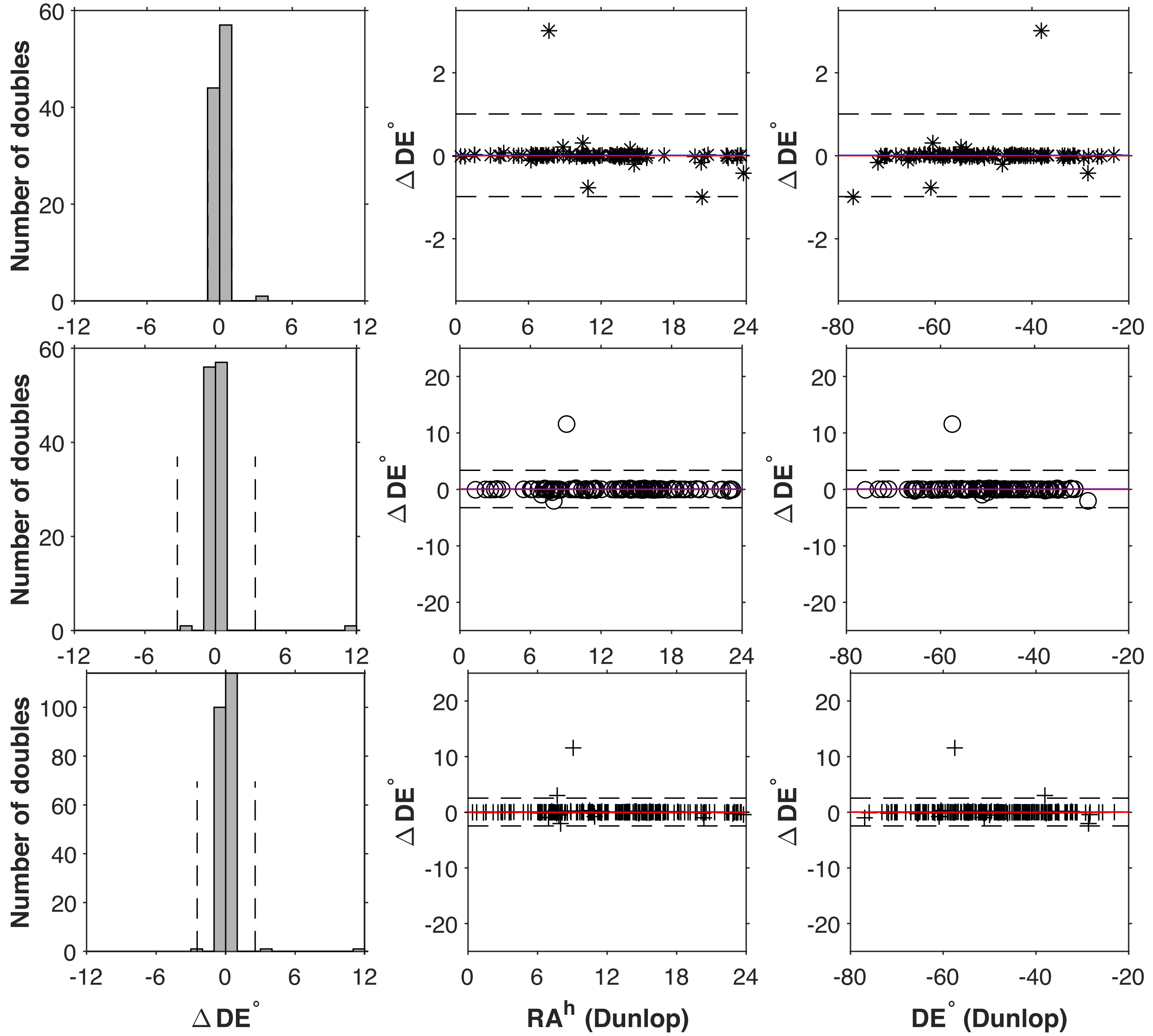


Figure 4. Accuracy of Dunlop's declinations without outliers removed. As per previous comments (Fig. 3). The 3σ dashed lines in the first histogram (top left) are present but follow very closely to the bin edges. Histogram bin widths are 1° in each case, and were chosen for plot clarity. Note the relatively few but large outliers. Most are probably due to typographical errors in the published catalogue (see Section 4.4). Note also the relative accuracy of declinations from the *Banks Refractor* (first row) as contrasted with those from the *Dunlop Refractor* (second row).

temporary equinox and epoch of 1825.0, as this is the equinox of the contemporary *Brisbane Catalogue*.

Each field was examined using the *Aladin Sky Atlas* (*Aladin*, Bonnarel et al. 2000) and overlaid with SIMBAD *Astronomical Database* (Wenger et al. 2000), ASCC-2.5 V3 (Kharchenko & Roeser 2009), and *Gaia DR2* (Gaia Collaboration 2018) data. In nearly all cases, the double star in question was within 10 arcmin of the forward precessed position (for further details see Section 4.2). For the few remaining, we extended the search out to a limit of 1°. To keep to a minimum poor or false identifications and by way of confirmation, a nearest neighbour search was also conducted with positions in the WDS, imposing a narrow magnitude tolerance on the primary and secondary of ±1 mag of Dunlop's published magnitudes and excluding first separations <2 arcsec, the minimum separation recorded by Dunlop. Any poor matches may be defined as *1st outliers* and *2nd outliers* in right ascension or declination (Section 4.4) or position angle or separation (Section 4.5) or magnitudes (Section 4.6).

The SIMBAD, ASCC-2.5 V3, and *Gaia DR2* source identifiers were recorded, together with International Celestial Reference System (ICRS) and epoch 2000.0 coordinates, proper motion, parallax, and photometric data from *Gaia DR2*. For the present purposes we take ICRS as equivalent to equatorial equinox J2000.0.

This research was well underway when *Gaia Early Data Release 3* (*Gaia EDR3*; Lindegren et al. 2021) became available. The authors acknowledge that the *Gaia EDR3* catalogue is comparably more precise than the *Gaia DR2* catalogue, however, this was found not to be significant enough to result in substantial differences of the outcomes presented in this paper. Both *Gaia DR2* and *Gaia EDR3* are

Table 5. Accuracy of Dunlop's right ascensions and declinations after rejection of *1st outliers*. The 2nd Gaussian bias and 1σ uncertainties do not reflect the Gaussian plots overlaying the histograms in Figs 3 and 4, which are for all available data *without* the removal of any outliers. The right ascension OLS slopes and R^2s are from RA (*Dunlop Catalogue*) versus RA (*Gaia DR2*) at 1826.0, after the removal of *1st outliers*. Similarly those for declination.

Banks Refractor	**Right ascension**	**Declination**
2nd Gaussian bias	$+0\overset{s}{.}4$	$-32''$
2nd Gaussian 1σ uncertainty	35^s	$371''$
1st outliers	92*, 105*	56*, 232*
2nd outliers	163*, 231*	92*,105*, 253*
2nd OLS slope	+0.9997	+0.9996
2nd OLS R^2	1	1
Dunlop Reflector	**Right ascension**	**Declination**
2nd Gaussian bias	-6^s	$-106''$
2nd Gaussian 1σ uncertainty	70^s	$804''$
1st outliers	75	75
2nd outliers	59, 118	37, 61
2nd OLS slope	+0.9999	+0.9963
2nd OLS R^2	1	1
Whole catalogue	**Right ascension**	**Declination**
2nd Gaussian bias	-4^s	$-88''$
2nd Gaussian 1σ uncertainty	56^s	$681''$
1st outliers	75, 118	56*, 75
2nd outliers	59, 92*	37, 61, 105*, 232*
2nd OLS slope	+0.9997	0.9990
2nd OLS R^2	1	1

known to be incomplete at the bright end (European Space Agency 2021), especially for close bright pairs. For the purpose of this paper, it is mainly the brighter end of the magnitudes that are required to compare against the *Dunlop Catalogue* (mean G of the Dunlop doubles is ~7, with a range from ~2.0 to ~12.2), which are available in *Gaia DR2*.

3.3 The *Dunlop Catalogue* equinox

There is no published equinox or epoch for the *Dunlop Catalogue* (except for nine double stars in the introduction to the *Dunlop Catalogue* for which epochs only are given, one during 1825 and eight during 1826). Using the data from *Gaia DR2*, we conducted a high precision backwards precession to the years between 1816 and 1836 in steps of 0.01 years for each primary, using the algorithms and rotation matrices from Eckardt & Humphrey (2017) and incorporating proper motion, parallax, and nutation effects. The separations between the original catalogue coordinate and the precessed *Gaia DR2* coordinate were calculated and the mean taken for each possible equinox. The stepped year with the lowest total separation we considered to be the working equinox of the *Dunlop Catalogue*, and the working epochs of observation for each double.

3.4 Positional accuracy

Given the *Gaia DR2* positions of the primary at the same equinox and epoch as the positions recorded in the *Dunlop Catalogue* we compared them (and all following comparisons) in the sense:

$$\Delta = \text{Dunlop} - Gaia\ DR2 \text{ (backwards precessed).} \quad (1)$$

The Δ in equation (1) should not be confused with Dunlop's limited use of Δ in columns 8 and 9 of the *Dunlop Catalogue*. We used three fitting models, Gaussian, ordinary least squares linear (OLS), and inverse power fits, and chose one of these to best reflect each set of parameters.

Two assumptions enabled us to pursue this method. The first is that both the primary and the secondary stars can be treated as independent entities with no connection between them (such as being gravitationally bound and therefore exhibiting orbital motion), and thus can be precessed separately. This assumption is reasonable as it is expected that most of the Dunlop double stars will be either optical double stars (displaying rectilinear motion of the secondary with respect to the primary) or if connected, the orbital period will be very long and the little movement of the secondary observed over the last 200 yr can be approximated by rectilinear motion. Dunlop's double stars have been observed extensively over the past 200 yr, and any detectable orbital motion may be expected to have already been reported with elements and plots in the *Sixth Catalog of Orbits of Visual Binary Stars* (Matson et al. 2020). To further support these assumptions, of the five Dunlop double stars which have entries in this catalogue, two have periods currently estimated in the thousands of centuries (Nos, 2* and 44), two (Nos, 5*, 23) have 'preliminary' orbits with periods of around 500 yr, and only one (No. 165*, α Cen) is a well accepted binary with a period of around 80 yr (see Appendix A).

The second assumption is that offsets (Gaussian biases and 1σ uncertainties) describe the accuracy of the measures in the *Dunlop Catalogue* only, the contribution due to uncertainties in the *Gaia DR2* data being insignificant compared with the Dunlop data. To illustrate this, we note that the positional (astrometric) accuracy of single stars in the 1820s was ~5 arcsec (Grosser 1979; Høg 2017). For early double star observations (of the early 19th century) the accuracy of the separations was ~0.5 arcsec, the accuracy of the position angle was ~4° (White, Letchford & Ernest 2018) and visual magnitudes were within 0.3 mag (Milone & Sterken 2011). On the other hand, *Gaia DR2* positional accuracy at ICRS and epoch 2015.5, is about 10^{-5} arcsec, with brighter stars having a slightly larger uncertainty (Gaia Collaboration2018). Even after precession, *Gaia DR2* errors are at least five orders of magnitude smaller than the 1820s uncertainties. We therefore designate the biases and uncertainties in the differences between the *Dunlop Catalogue* and precessed *Gaia DR2* astrometric positions as the bias and uncertainty in the *Dunlop Catalogue*.

3.5 Position angle and separation

Backwards precessing both the *Gaia DR2* primary and secondary positions using a high precision algorithm (Section 3.3), we compared Dunlop's *Mean PA* with those of precessed *Gaia DR2*, again in the sense of equation (1). Again, we applied single peak Gaussian fits, ordinary least squares linear (OLS), and inverse power fits, and chose one of these to best reflect each set of parameters.

3.6 Visual magnitudes

Gaia DR2 does not directly give apparent visual magnitudes. However, these can be approximated using conversion equations (Carrasco 2020) from the *G* (*G*-band mean magnitude) and the *BP*–*RP* colour (Integrated *BP* mean magnitude – Integrated *RP* mean magnitude) to the Johnson–Cousins (*V*) system, which is assumed to approximate the spectral response of the human eye. Magnitudes determined this way are here defined as *Gaia V*.

Again, the sense of comparison is similar to equation (1):

$$\Delta v\text{mag} = \text{Dunlop} - \text{Gaia } V. \quad (2)$$

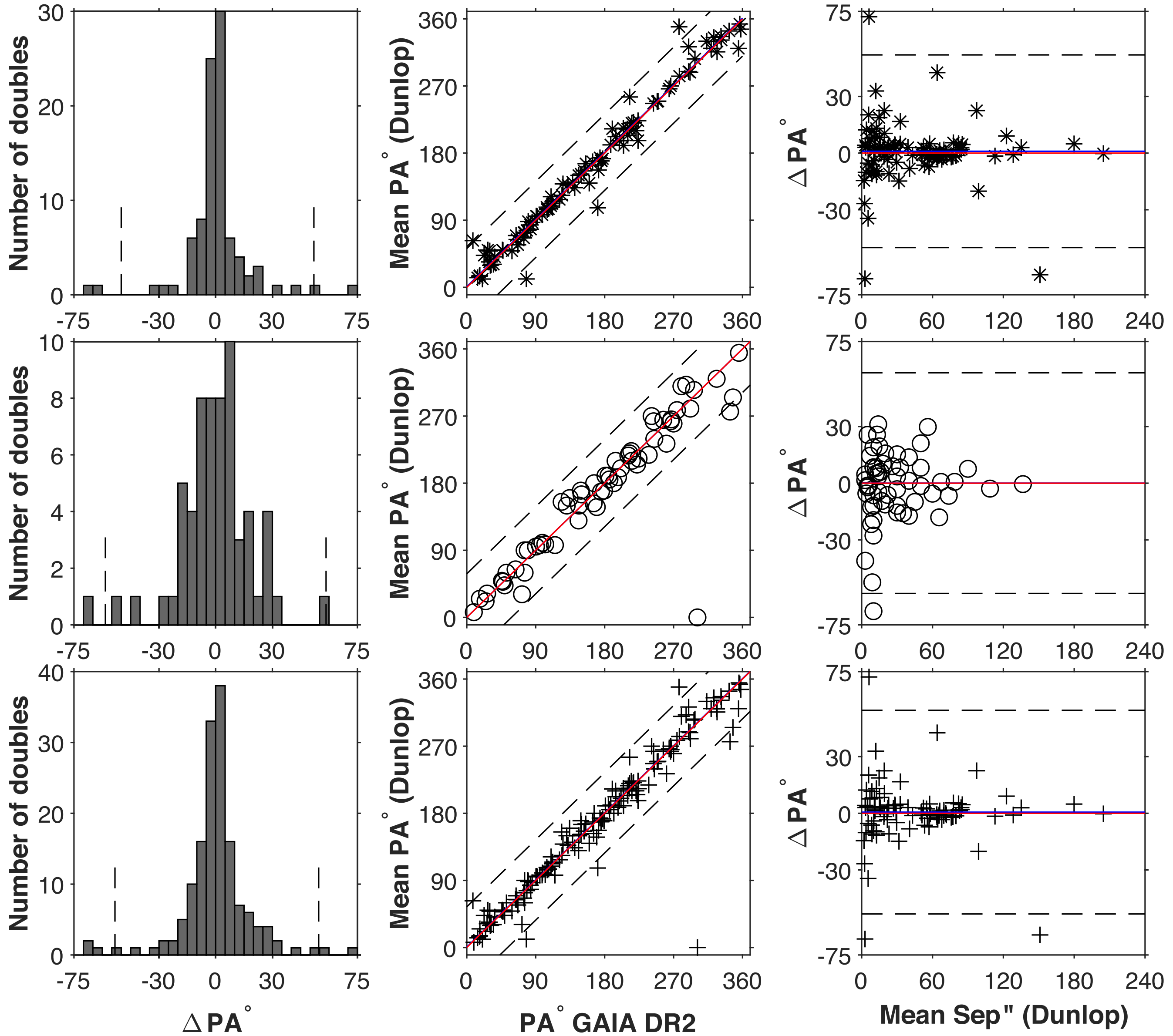


Figure 5. Accuracy of Dunlop's mean position angles with quadrant correction and without outliers removed. As per previous comments (Fig. 3), and histogram bin widths are 5° in each case, and were chosen for plot clarity. Note an increasing ΔPA with a decreasing *Mean Sep* (see Section 4.5).

3.7 Complications

There are three main complications associated with the analysis of the *Dunlop Catalogue*. The first is the fact that the *Dunlop Catalogue* is incomplete in many columns (Table 1). The second is that not all primaries and secondaries have *Gaia DR2* source identifiers and some with *Gaia DR2* source identifiers have incomplete data. Of the 253 entries in the *Dunlop Catalogue*, 221 primaries have *Gaia DR2* source identifiers, and 205 secondaries. The reasons why some stars do not have *Gaia DR2* source identifiers or have incomplete data include: they remain unidentified; they are too bright in the *G* band (*G* lower reliable limit is ≈3 mag, European Space Agency 2018); they are currently too close together (*Gaia DR2* has a lower limiting completeness separation of ≈2.2 arcsec, Gaia Collaboration2018). This means that not all double stars can be included in comparisons. In Section 4, we note the number of double stars available for comparison.

The third complication is that many of the measures in the *Dunlop Catalogue* have large outliers when equation (1) is applied to them. We define *1st outliers* as those beyond the Gaussian bias by more than three standard deviations, 3σ. All plots (Figs 2–9) include all available comparisons, without any outliers removed. We then removed these *1st outliers* and recalculated the second Gaussian bias and 1σ uncertainties. We defined *2nd outliers* as those beyond this second bias by more than 3σ. We further defined these second biases and 1σ uncertainties as those of the *Dunlop Catalogue* (see second assumption in Section 3.4). The OLS fits are taken from data with *1st outliers* removed.

4 RESULTS AND DISCUSSION

4.1 Internal consistency

The results of the internal consistency analysis of the measures in columns 5–9, resulting from observations made with the *Banks Re-*

Table 6. Accuracy of Dunlop's mean position angle and mean separation after quadrant error correction and rejection of *1st outliers*. See also comments for Table 5. C refers to the constant C in ΔPA = C/Sep and ΔSep = C/Sep (Sep = *Mean Sep*), which represent the inverse power fits for Dunlop's *Mean PA* and *Mean Sep*, respectively.

BanksRefractor	***Mean PA***	***Mean Sep***
2nd Gaussian bias	+1.1°	−1.7″
2nd Gaussian 1σ uncertainty	10.6°	17.8″
1st outliers	32∗, 39∗, 109∗, 252∗	79∗, 102∗, 109∗
2nd outliers	70∗, 78∗, 147∗	78∗, 183∗, 197∗, 216∗
2nd OLS slope	+0.9936	+0.8722
2nd OLS R^2	0.99	0.82
C (inverse power fit)	+57″°	+43″^{2}
Quadrants corrected	1∗, 5∗, 26∗, 45∗, 78∗, 87∗, 91∗, 99∗, 105∗, 111∗, 137∗, 141∗, 216∗, 235∗, 252∗	
Missing Quadrants supplied by precessed *Gaia DR2* PAs	27∗, 29∗, 36∗, 52∗, 88∗, 89∗, 253∗	
Dunlop Reflector	***Mean PA***	***Mean Sep***
2nd Gaussian bias	−0.2°	−9.7″
2nd Gaussian 1σ uncertainty	18.0°	14.5″
1st outliers	101, 151	230
2nd outliers	181	None
2nd OLS slope	+0.9823	+0.8254
2nd OLS R^2	0.97	0.75
C (inverse power fit)	+81″°	+ 58″^{2}
Quadrants corrected	14, 23, 59, 72, 181, 186, 188, 190, 192, 194, 200, 209, 211, 212, 224	
Missing Quadrants supplied by precessed *Gaia DR2* PAs	67, 68	
Whole catalogue	***Mean PA***	***Mean Sep***
2nd Gaussian bias	+1.2°	−4.1″
2nd Gaussian 1σ uncertainty	10.7°	16.6″
1st outliers	32∗, 39∗, 101, 109∗, 151, 252∗	79∗, 102∗, 109∗, 183∗
2nd outliers	23, 78∗, 181	78∗, 197∗, 216∗, 230
2nd OLS slope	+0.9893	+0.8830
2nd OLS R^2	0.98	0.81
C (inverse power fit)	+64″°	+48″^{2}

fractor, are given in Table 3. The Gaussian bias and 1σ uncertainties were calculated as given in Section 3.1, without any outliers removed. Insufficent data was available from the *Dunlop Reflector* to provide meaningful conclusions.

Nos. 76∗, 116∗, 127∗, and 176∗ had values in column 8 (ΔAR) of the *Dunlop Catalogue* that are larger than those in column 4 (Distance), and are probably due to transcription or typographical errors. They are individually explained in Appendix A. Table 3 shows that the *Angle of Pos* (column 5) and *Distance* (column 7) biases between duplicated measures from the *Banks Refractor* are generally less than one degree, and a few arcseconds, respectively. Those for ΔAR and ΔDeclin are less than a quarter of a sidereal second and a little over 1 arcsec, respectively.

Only five *1st outliers* were detected (Table 3, and individually in Appendix A). Three of those five (34∗ (*Distance*, column 7), 78∗, and 242∗) can be satisfactorily explained as due to probable typographical errors. Any effects that may be attributable to the multiple ways of calculating Dunlop's *Mean PA* and *Mean Sep* are therefore minimal.

4.2 Modern identification

Aside from the 168 entries in the *Dunlop Catalogue* with DUN as the discoverer designation, we found 35 that also appear in the WDS but with other discoverer designations, for example No. 1∗ we take to be 00315-6257 LCL 119AC (the A component is only ∼102 arcsec from Dunlop's precessed position). Eighteen remain unidentified, because no suitable (Section 3.2) candidate was found within 1° (however, see No. 90 in Appendix A). Fourteen are single stars with no suitable double star candidates within 1° (however, see Nos. 92∗, 96, and 208 in Appendix A). Eight were groupings of three to five stars, again with no suitable double star candidates within 1°. Poor matches are those defined in Section 3.2.

Nos. 56∗ and 61 fell outside the strict 1° search limit (Section 3.2), but we chose to accept the identifications given here (DUN 56 and DUN 61, respectively) as they are given both in SIMBAD and the WDS. No. 75 also fell beyond 1° and is listed in SIMBAD and the WDS as RMK 10. It can be explained as typographical errors in Dunlop's RA and DE (see Appendix A).

A total of 10 double stars (marked **two** in Table 4) that are not currently listed in the WDS were found. Seven were from the *Banks Refractor* (35∗, 112∗, 119∗, 149∗, 153∗, 164∗, and 252∗), and three from the *Dunlop Reflector* (37, 107, and 198). In addition, we corrected identification errors in Letchford et al. (2019b,c) for Nos. 13, 44, 54, 96, 116∗, 118, 136, 143∗, 167, 186, and 252∗. The corrections are also noted individually in Appendix A.

4.3 The *Dunlop Catalogue* equinox

The fractional year with the lowest mean angular distance between Dunlop primary positions and *Gaia DR2* precessed primary positions for each fractional year was J1826.05. See Fig. 2. This was calculated from 217 of the 253 primaries because not all primaries were found and not all found primaries had sufficient *Gaia DR2* data to be able to contribute to the calculations (Section 3.7). Since J1826.05 (JD 2388010) approximates B1826.0 (JD 2387992), we fix the catalogue equinox (and epochs) at 1826.0. This is consistent with what is known of Dunlop's observational schedule (Section 1) and eight of the nine epochs published in the introduction to the *Dunlop Catalogue* (Section 3.3). Here, we correct an error made in Letchford et al. (2019c) where we determined the *Dunlop Catalogue* equinox to be 1825.0.

4.4 Positional accuracy

Results of the positional accuracy of the *Dunlop Catalogue* as per Section 3.4 are shown here in Figs 3 and 4 and tabulated in Table 5. Note that both figures include all data without outliers removed. Of the seven outliers from the two telescopes in right ascension, six are probably due to typographical errors (59, 75, 105∗, 118, 163∗, 231∗), and one (92∗) was identified as a single star. As for the eight outliers in declination, six may be attributed to typographical errors (37, 61, 75, 92∗, 105∗, 232∗). Each of the eight outliers are individually discussed in Appendix A.

Primaries available for comparison were 102 (out of 119) for the *Banks Refractor* and 115 (out of 134) for the *Dunlop Reflector*. Just one (102∗ = 103∗) primary from the *Banks Refractor* was within 5 arcsec (1820s accuracy, and Section 3.4) of the modern precessed right ascension (RA) and none from the *Dunlop Reflector*. In declination (DE), there were four and eight primaries, respectively, whose declination is within 5 arcsec of the modern precessed declination (Appendix C). OLS fits showed that there is no dependence of right ascension on declination or vice versa for either telescope.

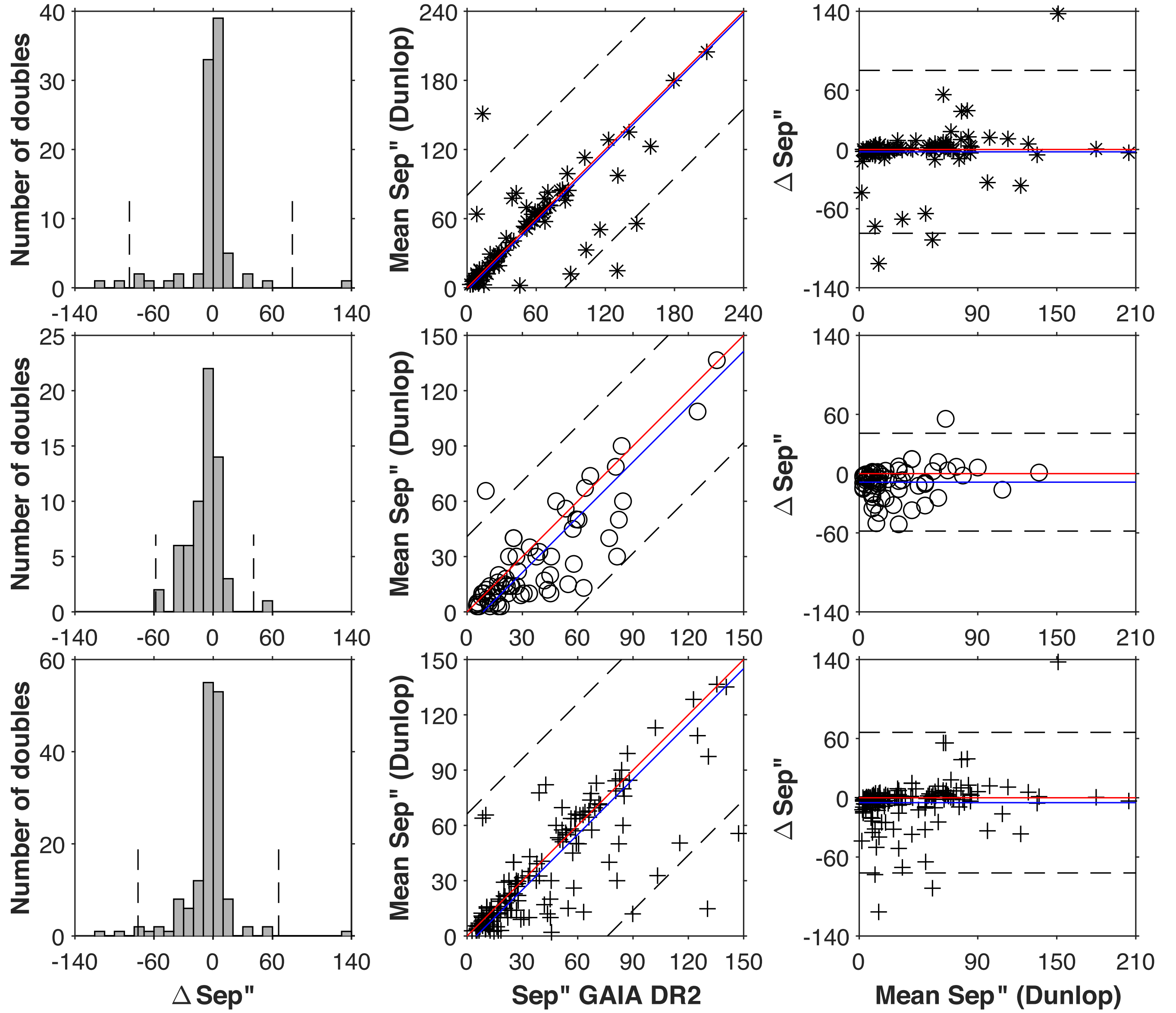


Figure 6. Accuracy of Dunlop's mean separations without outliers removed. As per previous comments (Fig. 3), and histogram bin widths are 10 arcsec in each case, and were chosen for plot clarity. Note a more linear relationship between ΔSep and *Mean Sep* in the third column, compared with ΔPA and *Mean Sep* in Fig. 5.

In general, the right ascensions in the *Dunlop Catalogue* are within 4 sidereal seconds of the *Gaia DR2* backwards precessed values, but with uncertainites approaching 1 sidereal minute. Right ascension biases from the *Banks Refractor* ($+0.4^{s}$) are 15 times better than those from the *Dunlop Reflector* (-6). Declinations are considerably worse from both telescopes. The *Banks Refractor* is better with a bias of $-32''$ and an uncertainty of $\pm 371''$, compared to the *Dunlop Reflector* with a bias of $-106''$ and a much larger uncertainty of $\pm 804''$.

4.5 Position angle and separation

Section 3.1 gave the process by which the *Mean PA* and *Mean Sep* were calculated and Quadrants identified in the *Dunlop Catalogue*. Initial results of position angle (PA) comparisons (93 and 62 double stars were available for comparison from the *Banks Refractor* and the *Dunlop Reflector*, respectively), showed that a significant number (16 from the *Banks Refractor* and 15 from the *Dunlop Reflector*), had Quadrants different from those of precessed *Gaia DR2* position angles. These differences were evenly spread such that north corrected to south (and vice versa) and following corrected to preceeding (and vice versa) occurred in about equal numbers for both telescopes. Six missing quadrants from the *Banks Refractor* and two from the *Dunlop Reflector* were supplied by precessed *Gaia DR2* position angles.

A quadrant correction was carried out on the *Dunlop Catalogue* by substituting the precessed *Gaia DR2* quadrants for those from the *Dunlop Catalogue*. After quadrant correction, the *Banks Refractor* had 44 (out of 93) double stars whose position angles fell within the expected 1820s accuracy of 4° (Section 3.4). The *Dunlop Reflector* had 14 (out of 62). These are listed in Appendix C. Fig. 5 shows the accuracy of Dunlop's *Mean PA*, *with* quadrant correction and no outliers removed. Table 6 quantifies the associated biases,

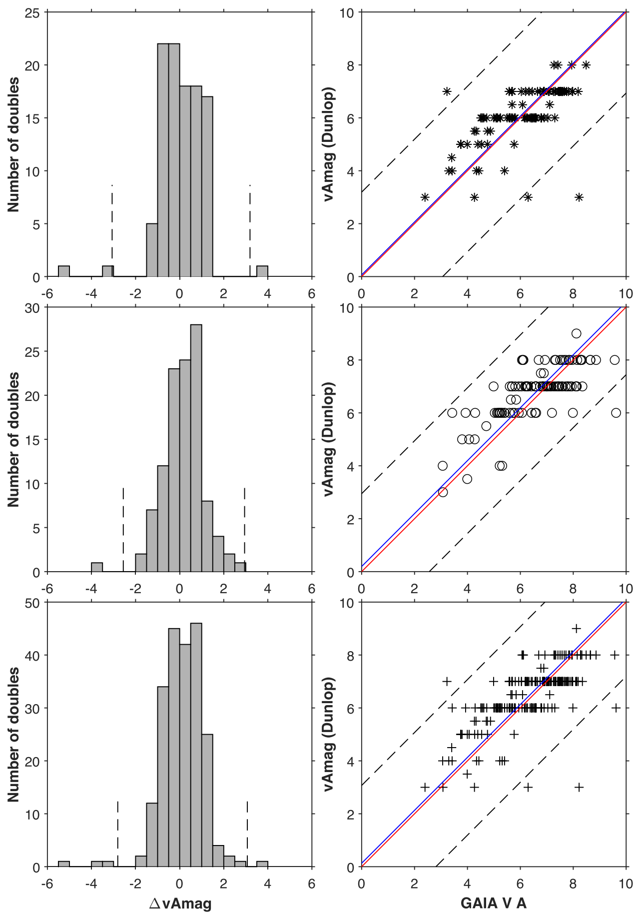


Figure 7. Accuracy of Dunlop's primary magnitudes without outliers removed. As per previous comments (Fig. 3), and histogram bin widths are 0.5 mag in each case, and were chosen for plot clarity. Note reasonably consistent spread of *vA* mag (Dunlop) with *Gaia V*A.

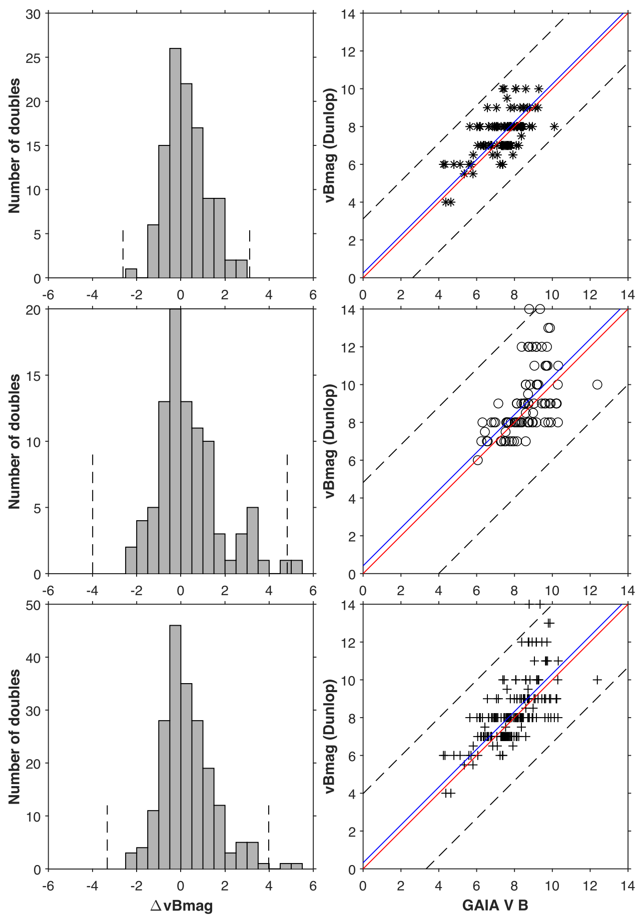


Figure 8. Accuracy of Dunlop's secondary magnitudes without outliers removed. As per previous comments (Fig. 3), and histogram bin widths are 0.5 mag in each case, and were chosen for plot clarity. Note increasing disparity of *vB* mag (Dunlop) with increasing *Gaia V*B.

uncertainties, OLS fits, and inverse power fits, lists the double stars whose quadrants were corrected, and lists quadrants supplied by *Gaia DR2*.

Dunlop's Mean PA bias for the *Banks Refractor*, after quadrant correction, is only a little over one degree ($+1.1^{\circ}$). The bias from the *Dunlop Reflector* is less at -0.2°. Of the ten *Mean PA* outliers (after Quadrant correction), three (78∗, 101, 252∗) may be attributed to typographical errors, and one (151) had a quadrant improvement from n to np. All ten are noted in Appendix A.

Selecting from the fitting models applied, the Gaussian bias best reflects the overall bias in *Mean PA*. An inverse power fit to ΔPA ($\sim\pm57^{\prime\prime\circ}$/*Mean Sep*$^{\prime\prime}$ and $\sim\pm81^{\prime\prime\circ}$/*Mean Sep*$^{\prime\prime}$ for the *Banks Refractor* and *Dunlop Reflector*, respectively), best reflects the reducing range of ΔPA with increasing *Mean Sep*, and serves as an approximate measure of the uncertainty of Dunlop's *Mean PA*.

Results for separations are shown in Fig. 6 and tabulated in Table 6. With regard to separations, the *Banks Refractor* had only 8 (out of 93) and the *Dunlop Reflector* only one (No. 213 out of 62) within the contemporary accuracy of 0.5 arcsec (Section 3.4). These are noted in Appendix A.

Separation biases were -1.7 and -9.7 arcsec from the *Banks Refractor* and *Dunlop Reflector*, respectively. The smallest Mean Sep was 2.0 arcsec from Nos. 24, 33, 50, 84∗, 132∗, 152, 170, and 173. The largest at 440 arcsec was from No. 125 (DUN 125AC). The corresponding separation from the precessed *Gaia DR2* positions for DUN 125AC could not be measured because component A (β Cru) does not have a *Gaia DR2* source identifier. Its *V* mag from SIMBAD is just 1.25.

The ΔSep range also reduces with increasing *Mean Sep*, though it is less pronounced than than of ΔPA (see Fig. 6, column 3). In a number of cases, ΔSep is larger than the *Dunlop Catalogue* separations themselves. Nevertheless, an OLS linear fit and associated uncertainty seems to be the best description of the *Mean Sep*. The slopes of the 2nd OLS linear fit of ΔSep versus *Mean Sep* with a point fixed at 0,0 is $+0.05$ for the *Banks Refractor* and -0.09 for the *Dunlop Refractor*. To reflect this, the Gaussian bias is the correction factor for all *Mean Sep*, and their uncertainties are ±0.05*Mean Sep*$^{\prime\prime}$ and ±0.09*Mean Sep*$^{\prime\prime}$, respectively (see Table 8).

Possible explanations for the eight separation outliers proved to be mixed. One could be a typographical error (78∗), one could be due to the high proper motion of component B (79∗), one has a complicated identification (102∗), and four are without adequate explanation (183∗, 197∗, 216∗, and 230).

The eighth separation outlier (*1st outlier*), No. 109∗, is particularly unusual. The *Dunlop Catalogue* recorded one estimate of the separation as $2^{\prime}\ 49.3^{\prime\prime}$ or $169.3^{\prime\prime}$ (the other estimate was calculated to be $132.8^{\prime\prime}$). The correct quadrant is recorded, also the magnitude estimates are approximately correct, but the modern precessed separation is only 13.5 arcsec. Also Dunlop's *Mean PA* (did not need Quadrant correction) is $\sim106.6^{\circ}$, *Gaia DR2* precessed

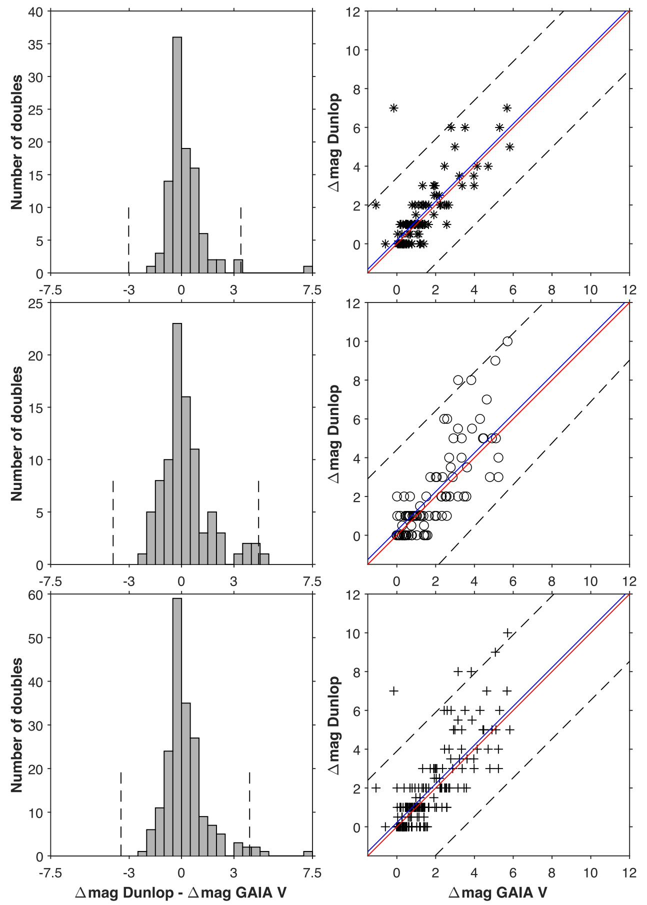


Figure 9. Accuracy of Dunlop's difference in magnitudes (primary–secondary) without outliers removed. As per previous comments (Fig. 3), and histogram bin widths are 0.5 mag in each case, and were chosen for plot clarity.

PA is ∼171.0°. There is no star with the right magnitude at Dunlop's separations from this primary.

4.6 Visual magnitudes

The results of comparing the Dunlop *eyeball* magnitude with the *Gaia V* magnitudes, for the primary star (ΔvA mag), the secondary star (ΔvB mag), in the sense of equation (2), and the differences between these two stars are shown in Figs 7, 8, and 9, respectively, and tabulated in Table 7.

The number of double stars available for comparison were 105 and 109 (out of 119) for the primary and secondary, respectively, using the *Banks Refractor*, and 112 and 94 (out of 134) for the primary and secondary, respectively, using the *Dunlop Reflector*. 16 and 32 primaries, respectively, had ΔvA mag within the contemporary accuracy of 0.3 mag (Section 3.4), and 23 and 16, respectively, had ΔvB mag within the contemporary accuracy of 0.3 mag. These are listed in Appendix C.

Dunlop's magnitude estimates had small biases but large uncertainties for both the primary and secondary components. Primary biases were +0.11 and + 0.23 mag, respectively, for the *Banks Refractor* and the *Dunlop Refractor* with uncertainties less than one magnitude at ±0.77 and ± 0.85 mag, respectively. Secondary biases were larger at +0.25 and +0.36 mag for the *Banks Refractor* and the *Dunlop Refractor*, respectively. Uncertainties were also larger at ±0.96 and ±1.39 mag, respectively. The Gaussian model seems to fit the data for both telescopes and the primaries and secondaries.

Table 7. Accuracy of Dunlop's magnitude estimates for the primary and secondary star, after rejection of *1st outliers*. See also comments for Table 5.

Primary	***Banks Refractor***	***Dunlop Reflector***	**Whole catalogue**
2nd Gaussian bias	+0.11	+0.23	+0.17
2nd Gaussian 1σ uncertainty	0.77	0.85	0.81
1st outliers	92∗, 98∗, 164∗	25	25, 92∗, 98∗, 164∗
2nd outliers	None	None	None
2nd OLS slope	+0.6124	+0.12	+0.6298
2nd OLS R^2	0.66	0.59	0.63
Secondary	***Banks Refractor***	***Dunlop Reflector***	**Whole catalogue**
2nd Gaussian bias	+0.25	+0.36	+0.28
2nd Gaussian 1σ uncertainty	0.96	1.39	1.13
1st outliers	None	51	51
2nd outliers	None	128	128
2nd OLS slope	+0.6639	+0.8415	+0.8078
2nd OLS R^2	0.40	0.32	0.46
Magnitude Differences	***Banks Refractor***	***Dunlop Reflector***	**Whole catalogue**
2nd Gaussian bias	+0.11	+0.20	+0.09
2nd Gaussian 1σ uncertainty	0.82	1.31	0.96
1st outliers	98∗	166	6, 51, 98∗, 128, 166
2nd outliers	9∗, 164∗	6, 51	9∗, 12, 164∗, 245
2nd OLS slope	+1.01	+1.18	+1.01
2nd OLS R^2	0.71	0.67	0.68

The outliers (25, 92∗, 98∗, 164∗ for the primary and 51 and 128 for the secondary) are difficult to explain. 98∗ and 128 may be due to variability and 164 may be due to errors in *Gaia DR2* colours, from which its visual magnitude was calculated. See Appendix A for details.

As seen in Fig. 8, we detect a clear trend of decreasing Dunlop magnitude with increasing *Gaia V* of the secondary.

We also note a near 1 to 1 relationship between Dunlop's difference in magnitude (primary–secondary) and *Gaia V* (primary–secondary) from 0 to a difference of about 2.5 mag, where Dunlop's differences increase (Fig. 9). The outliers (6, 9∗, 12, 51, 98∗, 164∗, and 166) are noted in Appendix A.

4.7 Recommendations

Table 8 contains the resulting recommended corrections and uncertainties from this work that should be applied to the *Dunlop Catalogue* prior to use in modern astrometry. The corrections and estimates of the uncertainties given for each measure are based on the comparison of the *Dunlop Catalogue* with the *Gaia DR2* release. Precise *Gaia DR2* identifications are given in the revised machine readable version of the *Dunlop Catalogue* (see Section 5, Data Availability).

We recommend no corrections to the right ascensions or declinations from the *Banks Refractor*. The right ascensions in the *Dunlop Catalogue* are given to whole sidereal seconds and the bias is less than half a sidereal second. Similarly the declinations are given in whole arcminutes and the bias is a little over half an

Table 8. Suggested corrections and uncertainties to be applied to the measures in the *Dunlop Catalogue*.

Banks Refractor	**Correction**	**1σ Uncertainty**
Right ascension	No correction	$\pm 35^{s}$
Declination	No correction	$\pm 6.2'$
Mean position angle	Subtract 1.1°	$\pm\sim 57''^{\circ}$/(*Mean Sep*$''$)
Mean separation	Add 1.7 arcsec	$\pm$0.05x*Mean Sep*$''$
Primary magnitude	No correction	$\pm$0.8 mag
Secondary magnitude	No correction	$\pm$1 mag
Dunlop Reflector	**Correction**	**1σ Uncertainty**
Right ascension	Add 6^{s}	$\pm 70^{s}$
Declination	Move north 1.8$'$	$\pm 13.4'$
Mean position angle	Add 0.2°	$\pm\sim 81''^{\circ}$/(*Mean Sep*$''$)
Mean separation	Add 9.7$''$	$\pm$0.09x*Mean Sep*$''$
Primary magnitude	No correction	$\pm$0.9 mag
Secondary magnitude	No correction	$\pm$1.4 mag

arcminute. Both have large uncertainites of 35^{s} and $371''$ or $6.2'$, respectively.

We recommend corrections to the right ascensions and declinations from the *Dunlop Reflector*. Right ascension should be increased on average by 6^{s} and the declinations should be moved north by $1.8'$. Again, both have large uncertainties of 70^{s} and $13.4'$, respectively.

The *Mean PA* have biases of $+1.1°$ and $-0.2°$ for the *Banks Refractor* and the *Dunlop Reflector*, respectively. However, the uncertainties vary such that, as might be expected, the *Mean PA* has an increasing uncertainty with decreasing *Mean Sep*. This is reflected in the power fit for the *Mean PA* uncertainties. The *Mean Sep* have corresponding biases of $-1.7''$ and $-9.7''$. Again, the Gaussian 1σ uncertainties do not adequately describe the *Mean Sep* uncertainites. A better model is an OLS linear fit where the uncertainites increase linearly as a fraction of the *Sep*.

With respect to Dunlop's magnitude estimates, we recommend no correction to them as they are given in whole magnitudes (except for the occasional half magnitude) and the biases are less than about a third of a magnitude. However, the uncertainties are significant.

4.8 A final note on the typographical errors

During the course of our study we uncovered a number of likely typographical errors in the published *Dunlop Catalogue*. These are found in Nos. 34∗, 37, 59, 61, 70∗, 75, 76∗, 78∗, 92∗, 97, 101, 105∗, 109∗, 116∗, 118, 127∗, 163∗, 176∗, 231∗, 232∗, and 242∗, and probably account for the outlier status of many of these. We were deliberately cautious in assigning typographical errors and so there are likely to be more.

How likely are such errors? Cozens (2008) detected a number of transcription errors in Dunlop's catalogue of southern nebulae (Dunlop 1828). A few decades later, Henry Chamberlain Russell, the Director of the Sydney Observatory, Australia (1870–1904) responded to Herschel's claims against the *Dunlop Catalogue* (Section 1) by pointing out that '[T]here are a good many very stupid mistakes in Herschel's own Catalogue' (Service 1890; Saunders 2004; Cozens et al. 2010), and that '[T]here are many stars in the Cape list that cannot be found' (Russell 1882). It would appear then, that meticulous proof reading was not always of a high standard at the time of Dunlop and Herschel.

5 CONCLUSIONS

We have drawn attention to and described, as well as corrected and estimated, the uncertainties of the measures in the first published catalogue of southern double stars, published by James Dunlop (Dunlop 1829).

We have identified a major source of the criticism of the *Dunlop Catalogue* (see Section 1) as errors in the quadrant designation of the secondary star. In Section 4.5, we have shown that 31 double stars in the *Dunlop Catalogue* contain quadrant errors. These have been rectified for individual double stars in Appendix A and in our revised machine readable version of the *Dunlop Catalogue* (see Section 5, Data Availability). The *Mean separations* were also far from consistent in quality. We have also highlighted that in this catalogue there are missing or incomplete data, some large uncertainties, subjective comments on some double stars, and even the deliberate (No. 3) inclusion of a supposedly single star.

Despite the acknowledged shortcomings of this catalogue, there can be no question that Dunlop's publication of the **first dedicated** catalogue of southern double stars is a major achievement and should be recognized as such. It represents the earliest astrometric and visual magnitude estimates of over 200 double stars in the Southern hemisphere. Measures associated with the double stars listed in Table C1 may be used for long period baseline astrometry. Other measures from the *Dunlop Catalogue* that do not constitute *1st outliers* or *2nd outliers* may also be used provided their uncertainties are taken into account.

ACKNOWLEDGEMENTS

We undertook this study out of respect for the pioneering work of our (albeit adopted) Australian pioneer scientist, James Dunlop. It is hoped that this study will lead to an improved recognition of his work, and that of Sir Thomas Makdougall Brisbane, Carl Rümker and the Parramatta Observatory. We acknowledge here previous work on old *single* star catalogues, especially that of Verbunt & van Gent (2010b), Verbunt & van Gent (2010a), Verbunt & van Gent (2011), Verbunt & van Gent (2012). Despite an extensive search, we are unaware of any other similar study on old *double* star catalogues. We also thank Professor Nick Lomb (Adjunct Professor, University of Southern Queensland) and Professor Tim Napier-Munn (Emeritus Professor, University of Queensland) and Allan Ernest (Adjunct Professor Charles Sturt University) for their suggestions early in the project. The authors also thank personal communications from Andrew James and Glen Cozens, and recognise the quality historic research being undertaken by both, and the web site of Andrew James (southastrodel.com). This research has made use of: NASA's Astrophysics Data System; the SIMBAD database, operated at CDS, Strasbourg, France; and the *Aladin sky atlas* developed at CDS, Strasbourg Observatory, France. The authors also wish to acknowledge and thank the anonymous reviewer for their impartial and thorough review and who supplied many helpful and insightful suggestions, all of which we have endeavoured to incorporate into the present paper.

DATA AVAILABILITY

Machine-readable data compiled by the first author is available online *here* as one file, but can be divided into three sections:

(i) The *Dunlop Catalogue* reproduced in digital form (columns 1–16).

(ii) Cross-matched identifications of the primary and secondary with: the identifier from the WDS; the discoverer code from the

WDS; SIMBAD, ASCC-2.5 V3, and *Gaia DR2* identifiers (columns 17–24).

(iii) Data generated from this paper (columns 25–33).

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SUPPORTING INFORMATION

Supplementary data are available at *MNRAS* online.

Supplementary material (online).xlsx

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APPENDIX A: SHORT NOTES ON SOME INDIVIDUAL DOUBLE STARS

The following are short notes on some of the Dunlop double stars.

No. 1∗ (LCL 119AC). Quadrant corrected from np to sf. Dunlop uncorrected *Mean PA* is ∼352.5°. Dunlop corrected *Mean PA* is ∼172.5°. Precessed *Gaia DR2* PA is ∼177.4°.

No. 2∗ (DUN 2). Grade 5 orbit in Matson et al. 2020, with a period of 5800 centuries. A grade 5 orbit is classified as 'Indeterminate', meaning that 'the elements may not even be approximately correct'.

No. 5∗ (DUN 5). Quadrant corrected from nf to sp. Also $|\Delta\mathrm{Sep}| >$ *Mean Sep*. Dunlop uncorrected *Mean PA* is ∼16.9°. Dunlop corrected *Mean PA* is ∼196.9°. Precessed *Gaia DR2* PA is ∼223.6°. Dunlop's PA in the WDS is 343.1° (np Quadrant). *Mean Sep* = 2.5 arcsec, *Gaia DR2* precessed separation is ∼14.6 arcsec. Explanation for both is that this is a known binary with a grade 4 orbit in Matson et al. 2020, with a period of 493.3 yr. A grade 4 orbit is classified as 'Preliminary', meaning that 'individual [orbital] elements entitled to little weight, and may be subject to substantial revisions'.

No. 6 (DUN 6AB). *2nd outlier* in vB – vA. Component A is ϕ Eri and component B is CD-52 465. Dunlop's vA = 4 and vB = 12. *Gaia DR2* calculated vA is ∼5.31 and calculated vB is ∼9.15.

No. 9∗ (PZ 2). *2nd outlier* in vB – vA. Component A is θ01 Eri and component B is θ02 Eri. Dunlop's vA = 4 and vB = 6. *Gaia DR2* calculated vA is ∼5.40 and vB is ∼4.33. Both are high proper motion stars according to SIMBAD.

No. 12 (DUN 12A,BC). *2nd outlier* in vB – vA with respect to the whole catalogue. Component A is HD 20586 (high proper motion star) and component B is CCDM J03152−6427BC (double star). Dunlop's VA = 6 and vB = 12. *Gaia DR2* calculated vA is ∼6.56 and calculated vB is ∼9.15.

No. 13 (unidentified). Incorrectly identified in Letchford et al. (2019b,c) as being from the *Banks Refractor*. Position and magnitudes come from the *Dunlop Reflector*.

No. 14 (DUN 14). Quadrant corrected from np to sp. Dunlop uncorrected *Mean PA* is ∼280.0°. Dunlop corrected *Mean PA* is ∼260.0°. Precessed *Gaia DR2* PA is ∼269.9°.

No. 15∗ (DUN 15). Also |ΔSep| > *Mean Sep*. *Mean Sep* = 4 arcsec, *Gaia DR2* precessed separation is ∼10.1 arcsec.

No. 23 (DUN 23). Quadrant corrected from np to nf. *2nd outlier* in *Mean PA* with respect to the whole catalogue. Dunlop uncorrected *Mean PA* is ∼329.0°. Dunlop corrected *Mean PA* is ∼31.0°. Precessed *Gaia DR2* PA is ∼72.1°. However, this is a known binary with a grade 4 orbit in Matson et al. 2020 (refer to No 5∗), with a period of 552.8417 yr. Dunlop's PA in the WDS is 329° (np Quadrant).

No. 25 (JSP 96). *1st outlier* in vA. Component A is CD-32 2930A. Dunlop's vA = 6, *Gaia DR2* calculated vA ∼ 9.62. Not noted as a variable in SIMBAD.

No. 26∗ (DUN 26AB). Quadrant corrected from nf to sf. Dunlop uncorrected *Mean PA* is ∼67.8°. Dunlop corrected *Mean PA* is ∼112.2°. Precessed *Gaia DR2* PA is ∼111.6°.

No. 27∗ (DUN 27AB). Missing Quadrant in the *Dunlop Catalogue* and therefore no *Mean PA*. The *Gaia DR2* Quadrant is sp. Thus Dunlop's corrected *Mean PA* is 223.3°. Precessed *Gaia DR2* PA is ∼223.6°.

No. 29∗ (DUN 29). Missing Quadrant in the *Dunlop Catalogue* and therefore no *Mean PA*. The *Gaia DR2* Quadrant is sf. Thus Dunlop's corrected *Mean PA* is 109.1°. Precessed *Gaia DR2* PA is ∼109.9°.

No. 32∗ (DUN 32). *1st outlier* in corrected PA. Component A is HD 48543A, component B is HD 48543B. Dunlop's *Mean PA* (did not need Quadrant correction) is ∼349.3°, *Gaia DR2* precessed PA is ∼277.2°.

No. 34∗ (DUN 34). *1st outlier* in *Angle of Pos* (column 5). *Angle of Pos* is 85° 14 arcmin. The angle of position calculated from the *Distance* (column 7) and Δ *Declin* (column 9) is ∼57.5°. Dunlop's *Distance* (column 7) is an *1st outlier*. *Distance* is 2 arcmin 10.15″ (130.15″). The *Mean Sep* is 1′ 37.″4 (97.″4), where the other measure of separation can be calculated from the *Angle of Pos* and Δ *Declin* and is ∼1′ 4.″6 (64.″6). Perhaps a typographical error (2 arcmin instead of 1 arcmin).

No. 36∗ (H 5 108A,BC). Missing Quadrant in the *Dunlop Catalogue* and therefore no *Mean PA*. The *Gaia DR2* Quadrant is nf. Thus Dunlop's corrected *Mean PA* is 69.4°. Precessed *Gaia DR2* PA is ∼64.4°.

No. 37 (two). *1st outlier* in DE. Component A is HD 53142. Dunlop's DE is ∼ −51° 9 arcmin. Not noted in SIMBAD as a high proper motion star. This is the same primary as BRI 1456 in the *Brisbane catalogue* (Richardson & Brisbane 1835). There the declination is S.P.D. (South Polar Distance) 39° 46′ 55.″6 or DE ∼ −50° 13′. Could be the result of a typographical error, where −51° should be −50°.

No. 39∗ (DUN 39). *1st outlier* in corrected PA. Component A is HD 53921A, component B is HD 53921B. Dunlop's *Mean PA* (did not need Quadrant correction) is ∼11.23°, *Gaia DR2* precessed PA is ∼77.7°. Curiously, the *Angle of Pos* is given as 78° 48′ (78.8°), close to the *Gaia DR2* precessed PA, yet both Dunlop and *Gaia DR2* agree that the Quadrant is nf (north following).

No. 44 (RMK 6AB). The name of the double in the WDS is RMK 6AB, with a grade 5 orbit in Matson et al. 2020 (refer to No. 2∗), with a period of 10 000 centuries. The discoverer code 'RMK' means that the WDS attributes the discovery of the double to Carl Rümker of the Parramatta Observatory, and not to James Dunlop. Incorrectly labelled as 'unidentified' in Letchford et al. (2019b, c). The WDS system identifier is 07204-5219.

No. 45∗ (DUN 45). Quadrant corrected from nf to sf. Dunlop uncorrected *Mean PA* is ∼14.2°. Dunlop corrected *Mean PA* is ∼165.8°. Precessed *Gaia DR2* PA is ∼155.4°.

No. 51 (DUN 51). *1st outlier* in vB. *2nd outlier* in vB – vA. Component A is sig Pup and component B is sig Pup B. Dunlop's vA = 4 and vB = 14. *Gaia DR2* calculated vA is ∼3.06 and calculated vB is ∼8.77. Both noted in SIMBAD as high proper motion stars, but not as variables. *Gaia DR2* precessed Quadrant is nf. Dunlop PA remains 90°.

No. 52∗ (H N 19). Missing Quadrant in the *Dunlop Catalogue* and therefore no *Mean PA*. The *Gaia DR2* Quadrant is sf. Thus Dunlop's corrected *Mean PA* is 105.4°. Precessed *Gaia DR2* PA is ∼105.3°.

No. 53∗ (H 3 27AB). *1st outlier* in corrected PA. Component A is κ02Pup, component B is κ01Pup. Dunlop's *Mean PA* (did not need Quadrant correction) is ∼315.8°, *Gaia DR2* precessed PA is ∼326.8°.

No. 54 (one). Incorrectly identified in Letchford et al. (2019b, c) as being from the *Banks Refractor*. Measures come from the *Dunlop Reflector*.

No. 56∗ (DUN 56). *1st outlier* in DE. Component A is HD 63425. Dunlop's DE is −38° 4′, *Gaia DR2* precessed is ∼-41° 04′ 45.″71. Difference ∼ + 2.9°. In the WDS as DUN 56. Not noted as a high proper motion star in SIMBAD.

No. 59 (DUN 59). *2nd outlier* in RA. Quadrant corrected from sf to nf. Component A is HD 66005. Dunlop's AR (RA) = 7^h 50^m 30^s, *Gaia DR2* precessed RA is ∼7^h 54^m 20^s. Difference is ∼−0.6° (−230). Not noted by SIMBAD as a high proper motion star. May be a typographical error, 50^m should be 54^m. Dunlop uncorrected *Mean PA* is ∼131.0°. Dunlop corrected *Mean PA* is ∼49.0°. Precessed *Gaia DR2* PA is ∼45.91°.

No. 61 (DUN 61). *2nd outlier* in DE. Component A is HD 67409. Dunlop's DE is −28° 39′ and the precessed *Gaia DR2* DE is ∼ −26° 37′ 9″. Probably a typographical error. −28° should be −26°. Not noted by SIMBAD as a high proper motion star.

No. 64∗ (DUN 65AC) and 65∗ (DUN 65AB). A group of stars associated with γ Argus, now γ Velorum. The identification of these pairs is made difficult by the fact that Dunlop recorded both as having the same right ascension and declination. We base our identification on his magnitude estimates: 2.3 and 8 for DUN 64∗ and 2.3 and 6 for DUN 65∗. Thus: DUN 64 AC and DUN 65 AB are the respective discoverer and component codes.

No. 67 (DUN 67). Missing Quadrant in the *Dunlop Catalogue* and therefore no *Mean PA*. The *Gaia DR2* Quadrant is sf. Thus Dunlop's corrected *Mean PA* is 168.6°. Precessed *Gaia DR2* PA is ∼175.3°.

No. 68 (DUN 68). Missing Quadrant in the *Dunlop Catalogue* and therefore no *Mean PA*. The *Gaia DR2* Quadrant is nf. Thus Dunlop's corrected *Mean PA* is $\sim$21.7°. Precessed *Gaia DR2* PA is $\sim$24.6°.

No. 70∗ (DUN 70). *2nd outlier* in corrected PA (did not need Quadrant correction). Component A is HD 72127A and component B is HD 72127B. Dunlop's *Mean PA* is 320.3° and the precessed *Gaia DR2* PA is $\sim$354.8°. Neither components are high proper motion stars according to SIMBAD. Dunlop's *Mean PA* could only be calculated one way, via *Angle of Pos* (50° 18′) and *Quadrant.* (np). Perhaps Dunlop's 50° is a typographical error and should be 54°.

No. 72 (DUN 72A,BC). Quadrant corrected from nf to np. Dunlop uncorrected *Mean PA* is $\sim$5.2°. Dunlop corrected *Mean PA* is $\sim$354.8°. Precessed *Gaia DR2* PA is $\sim$355.3°.

No. 75 (RMK 10). *1st outlier* in RA. *1st outlier* in DE. Component A is HD 80807. Dunlop's RA and DE are 9^{h} 4^{m} 19^{s} and −57° 30′, respectively. *Gaia DR2* precessed RA and DE are 09^{h} 15^{m} $49^{s}.25$ and −69° 04′ $11''.93$, respectively. Not noted as a high proper motion star. There may be a typographical error in Dunlop's RA minutes (should be 14^{m} instead of 4^{m}), and there may be a typographical error in Dunlop's DE degrees (should be −67° instead of −57°).

No. 76∗ (DUN 76AC). Dunlop's ΔAR (6.265^{s}, or 66.740″, column 8) is larger than his *Distance* (61.40″). Probably a typographical error.

No. 78∗ (DUN 78). *1st outlier* in ΔAR (column 8). *2nd outlier* in corrected PA (needed Quadrant correction). *2nd outlier* in Sep. ΔAR is 0.5^{s}. ΔAR calculated via the *Mean PA*, *Mean Sep* and declination (column 4) is $\sim$4.8^{s}. Dunlop's uncorrected *Mean PA* is 75.3° and the precessed *Gaia DR2* PA is $\sim$212.7°. Dunlop's *Quadrant.* was corrected from nf to sp. Dunlop's corrected *Mean PA* was 255.3°, or an *Angle of Pos* of 14° 42′. Dunlop's original *Angle of Pos* of 1° 7′ probably should be 14° 7′, a likely typographical error. Dunlop's *Mean Sep* is $\sim$63.9″. *Gaia DR2* precessed Sep is $\sim$8.43″. Perhaps Dunlop's *Mean Sep* should be $\sim$6.39″.

No. 79∗ (DUN 79). *1st outlier* in Sep. Also $|\Delta\mathrm{Sep}| >$ *Mean Sep*. Component A is HD 82965, component B is HD 82986. Dunlop's *Mean Sep* is $\sim$14.8″. *Gaia DR2* precessed Sep. is $\sim$130.40″. According to SIMBAD, component B is a high proper motion star. Note that Dunlop's *Mean PA* is $\sim$48.7°, but the calculated *Gaia DR2* precessed PA is $\sim$30.00°.

No. 80 (DUN 80AB). Also $|\Delta\mathrm{Sep}| >$ *Mean Sep*. *Mean Sep* = 3″, *Gaia DR2* precessed Sep $\sim$ 18.4″. Perhaps Dunlop's should have been 13″.

No. 84∗ (HJ 4282). Also $|\Delta\mathrm{Sep}| >$ *Mean Sep*. *Mean Sep* = 2.0″, and *Gaia DR2* precessed separation is $\sim$45.8″. Component A is HD 87364, component B is HD 298817. There must be an error in Dunlop's Distance (column 7). Perhaps it should read 42″.

No. 87∗ (DUN 87). Quadrant corrected from sp to np. Dunlop uncorrected *Mean PA* is $\sim$203.6°. Dunlop corrected *Mean PA* is $\sim$336.4°. Precessed *Gaia DR2* PA is $\sim$331.9°.

No. 88∗ (PZ 3). Missing Quadrant in the *Dunlop Catalogue* and therefore no *Mean PA*. The *Gaia DR2* Quadrant is sp. Thus Dunlop's corrected *Mean PA* is $\sim$221.1°. Precessed *Gaia DR2* PA is $\sim$217.7°.

No. 89∗ (DUN 89AB). Missing Quadrant in the *Dunlop Catalogue* and therefore no *Mean PA*. The *Gaia DR2* Quadrant is nf. Thus Dunlop's corrected *Mean PA* is $\sim$34.0°. Precessed *Gaia DR2* PA is $\sim$29.6°.

No. 90 (unidentified). The only WDS double star within 1° of Dunlop's position precessed to 2000.0 is No. 89∗. It is possible that No. 90 = No. 89∗, especially considering they were both discovered using different telescopes. At the present, we prefer to continue to classify No. 90 as unidentified.

No. 91∗ (DUN 91). Quadrant corrected from sp to nf. Also $|\Delta\mathrm{Sep}|$ $>$ *Mean Sep*. Dunlop uncorrected *Mean PA* is $\sim$228.8°. Dunlop corrected *Mean PA* is $\sim$48.8°. Precessed *Gaia DR2* PA is $\sim$59.0°. *Mean Sep* = 3.69″ and precessed *Gaia DR2* Sep is $\sim$9.94″.

No. 92∗ (one). *1st outlier* in RA. *2nd outlier* in DE. *1st outlier* in vA. Only one star was detected in the approximate Dunlop position, namely p Car (HD 91465). Dunlop's vA = 7. The nearest suitable double star to the forward precessed Dunlop position in the WDS is DUN 87 at a distance of $\sim$3500″. *Gaia DR2* calculated vA $\sim$3.23. No. 92∗ could be the pair HD 91270 (A) and HD 91269 (B), which are in the WDS as 10307-6121, however, they are $\sim$22.5 arcmin (1350″) from p Car. Dunlop's Sep bias from the *Banks Refractor* is −2.4″ and his Sep uncertainty just ±27.5″. Dunlop's RA = 10^{h} 29^{m} 33^{s}, *Gaia DR2* precessed RA is $\sim 10^{h}$ 25^{m} $53^{s}.74$. Dunlop's DE is −60° 29′ and the precessed *Gaia DR2* DE is $\sim$ −60° 47′ 25″. Difference is $\sim$ +18.4′. Could be typographical error, 49 arcmin instead of 29 arcmin.

No. 96 (one). Incorrectly identified in Letchford et al. (2019b,c) as being from the *Banks Refractor*. Measures come from the *Dunlop Reflector*. The nearest suitable double star in the WDS is HJ 4366 at a distance of $\sim$3440″. Both the forward precessed Dunlop position and HJ 4366 are in dense star fields, making it difficult to discern what Dunlop may have meant.

No. 97 (DUN 97AB). Also $|\Delta\mathrm{Sep}| >$ *Mean Sep*. *Mean Sep* = 3″, *Gaia DR2* precessed Sep $\sim$ 12.5″. Perhaps there is a typographical error here and Dunlop's *Distance* (column 7) should have been 13″ instead of 3″.

No. 98∗ (DUN 98AH). *1st outlier* in vA. *1st outlier* in vB - vA. Component A is η Car, component B is HD 303308. Dunlop's vA = 3 and vB = 10. *Gaia DR2* calculated vA is $\sim$8.22 and calculated vB $\sim$8.06. According to SIMBAD component A is an emission line star, and therefore possibly variable.

No. 99∗ (DUN 99AB). Quadrant corrected from sp to nf. Dunlop uncorrected *Mean PA* is $\sim$253.6°. Dunlop corrected *Mean PA* is $\sim$73.6°. Precessed *Gaia DR2* PA is $\sim$74.4°.

No. 101 (HJ 4378). *1st outlier* in corrected PA. Also $|\Delta\mathrm{Sep}| >$ *Mean Sep*. Component A is HD 94173, and component B is CPD-59 2783. Dunlop's *Mean PA* = 276°, the PA from precessed *Gaia DR2* is $\sim$343°.8. Both in same Quadrant, so No. 101 was not Quadrant corrected. May be a typographical error. Dunlop's *Angle of Pos* is 6° 0′ and perhaps should have been 76° 0′. Neither are noted as high proper motion stars in SIMBAD. *Mean Sep* = 10″, *Gaia DR2* precessed Sep $\sim$ 30.8″.

No. 102∗ (DUN 102AB). *1st outlier* in Sep. Also $|\Delta\mathrm{Sep}| >$ *Mean Sep*. Component A is u Car, component B is HD 94491. Mean Dunlop Sep is $\sim$55.6″, *Gaia DR2* precessed Sep is $\sim$147.25″. Note component C is CPD-58 2836, which together with u Car (HD 95109) form No. 103∗. Dunlop's *Mean Sep* for AC is $\sim$57.5″. Our identification is based on the fact that Dunlop identified 102∗ as AB and 103∗ as AC, relying on his apparent visual magnitude estimates: vA = 5, vB = 7, and vC = 8.

No. 105∗ (DUN 105). *1st outlier* in RA. *2nd outlier* in DE. Quadrant corrected from sf to sp. In the WDS as DUN 105. Component A is HD 96264. Dunlop's right ascension = 10^{h} 55^{m} 21^{s}, *Gaia DR2* precessed RA is $\sim 10^{h}$ 57^{m} $47^{s}.71$. Difference is −146.7^{s} (−1096.6″). Dunlop's declination is −60° 53′ and the *Gaia DR2* precessed DE is −60° 6′ 43″. Right ascension and declination could be a typographical errors, right ascension should be 57′ instead of 55′, declination should be 3′ instead of 53′. Not noted by SIMBAD as a high proper motion star. Dunlop uncorrected *Mean PA* is $\sim$149.9°. Dunlop corrected *Mean PA* is $\sim$210.1°. Precessed *Gaia DR2* PA is $\sim$221.0°.

No. 109∗ (BSO 6). *1st outlier* in Sep. *1st outlier* in corrected PA. Component A is HD 99803, component B is CD-41 6565B (HIP 56001). Dunlop's *Mean Sep* is ∼151.0″ and the *Gaia DR2* precessed Sep is ∼13.51″. Dunlop's *Mean Sep* is the average of two different values: 2′ 49.3″ (169.3″) given in column 5 (distance) and column 9 (Δ*Declin*) value of 42.46″ divided by the sine of the *Angle of Pos* (column 5) which yields 132.78″. Thus any typographical errors would require errors in more than one column value. Also Dunlop's *Mean PA* (did not need Quadrant correction) is ∼106.6°, *Gaia DR2* precessed PA is ∼171.0°. There is no star with the right magnitude at 169″ from the primary.

No. 111∗ (H 3 96). Quadrant corrected from nf to sp. Dunlop uncorrected *Mean PA* is ∼23.9°. Dunlop corrected *Mean PA* is ∼203.9°. Precessed *Gaia DR2* PA is ∼210.2°.

No. 114 (DUN 114). Also |ΔSep| > *Mean Sep*. *Mean Sep* = 3″, *Gaia DR2* precessed Sep ∼ 16.9″. Perhaps Dunlop's should have been 13″.

No. 116∗ (DUN 116AB). Dunlop's Δ*AR* (1.6^s, or 20.50″, column 8) is larger than his *Distance* (15.2″). Probably a typographical error. ASCC and *Gaia DR2* source identifiers of components in Letchford et al. (2019b,c) swapped.

No. 118 (HJ 4500). Incorrectly identified in Letchford et al. (2019b,c) as 'two'. Here we identify it as HJ 4500. *2nd outlier* in RA. Component A is HD 106132. Dunlop's RA is 12^h 02^m 00^s, *Gaia DR2* precessed RA is 12^h 16^m 56^s. Probably a typographical error. Dunlop's 02^m should be 20^m.

No. 122∗ (DUN 252AC) and 123∗ (DUN 252AB). Listed in the WDS as DUN 252AC and DUN 252AB, respectively, i.e. α01 Cru (α Crucis), both with WDS 12266-6306.

No. 127∗ (DUN 127). The *Dunlop Catalogue* Δ*AR* (1.17^s, or 10.08″, column 8) is larger than its *Distance* of 10″. Probably a typographical error.

No. 128 (DUN 128). *1st outlier* in vB. *1st outlier* in vB – vA with respect to the whole catalogue. Component A is ξ02 Cen (spectroscopic binary) and component B is V1261 Cen (rotationally variable star). Dunlop's vA = 5 and vB = 14. *Gaia DR2* calculated vA is ∼4.27 and calculated vB is ∼9.35.

No. 136 (unidentified). Incorrectly identified in Letchford et al. (2019b,c) as the double star SEE 179. SEE 179 or d Cen had a separation at epoch 2017 of 0.2″, well below Dunlop's resolution and that of *Gaia DR2*.

No. 137∗ (DUN 137). Quadrant corrected from nf to np. Dunlop uncorrected *Mean PA* is ∼13.9°. Dunlop corrected *Mean PA* is ∼346.1°. Precessed *Gaia DR2* PA is ∼357.8°.

No. 140 (DUN 140). *Gaia DR2* precessed Quadrant is nf. Dunlop PA remains 90°.

No. 141∗ (DUN 141). Quadrant corrected from sp to sf. Dunlop uncorrected *Mean PA* is ∼191.6°. Dunlop corrected *Mean PA* is ∼168.4°. Precessed *Gaia DR2* PA is ∼164.3°.

No. 143∗ (DUN 143). Incorrectly identified in Letchford et al. (2019b,c) as being from the *Dunlop Reflector*. Measures come from the *Banks Refractor*.

No. 145 (DUN 145). Also |ΔSep| > *Mean Sep*. *Mean Sep* = 10″, *Gaia DR2* precessed Sep ∼ 22.1″. Perhaps Dunlop's should have been 20″.

No. 147 (RMK 18). *1st outlier* in corrected PA. Dunlop's *Mean PA* did not need Quadrant correction, and is ∼322.5°. *Gaia DR2* precessed PA is ∼289.7°.

No. 151 (DUN 151AB). *1st outlier* in corrected PA. Component A is HD 121504, component B is CPD-55 5793. Dunlop's *Mean PA* = 0°, as only the Angle of Pos. (90° 0′) and Quadrant (n) columns have data. *Gaia DR2* precessed PA is ∼301.14° (Quadrant np). ΔPA = 360 − 301.1° ≈ +58.9°. According to SIMBAD, HD 121504 is a high proper motion star. Dunlop PA remains 0°.

No. 157 (HJ 4651). Also |ΔSep| > *Mean Sep*. *Mean Sep* = 13″, *Gaia DR2* precessed Sep ∼ 63.2″.

No. 162 (DUN 162). *Gaia DR2* precessed Quadrant is sp. Dunlop PA remains 270°.

No. 163∗ (DUN 163). *2nd outlier* in RA. Component A is HD 128291. Dunlop's RA = 14^h 23^m 52^s, *Gaia DR2* precessed RA is ∼14^h 25^m 50^s. Difference is ∼−0.3° (−120). Noted by SIMBAD as a high proper motion star. May be a typographical error, 23^m should be 25^m.

No. 164∗ (two). *1st outlier* in vA. *2nd outlier* in vB – vA. Component A is η Cen, a Be star, component B is HD 127992. Dunlop's vA = 3 and vB = 9. *Gaia DR2* calculated vA is ∼6.29 (SIMBAD vA = 2.31) and calculated vB is ∼9.09 (SIMBAD vB = 9.19). Could be due to an error in *Gaia DR2* colours for this star.

No. 165∗ (RHD 1AB). Discoverer code in the WDS is RHD 1AB (α Cen), with a grade 2 orbit in Matson et al. (2020), with a period of 79.91 yr. A grade 2 orbit is classified as 'Good', meaning 'most of a revolution, well observed, with sufficient curvature to give considerable confidence in the derived elements'.

No. 166 (DUN 166AB). *1st outlier* in vB – vA. Dunlop's vA = 4 and vB = 12. Component A is α Cir A (Variable Star of α2 CVn type) and component B is α Cir B. *Gaia DR2* calculated vA is ∼5.22 and calculated vB is ∼8.38.

No. 167 (SKF 1973). Incorrectly identified in Letchford et al. (2019b,c) as 'two' stars not previously recorded in the WDS. It is 14410-3608 SKF 1973.

No. 176∗ (DUN 176). Dunlop's Δ*AR* (7.385^s, or 69.04″, column 8) is larger than his *Distance* (68.79″). Probably a typographical error.

No. 178∗ (DUN 178AC). Dunlop's Δ*AR* (column 8) is a *1st outlier*. Δ*AR* is 3.525^s. The calculated Δ*AR* [calculated via the *Mean PA*, *Mean Sep*, and declination (column 4)] is ∼7.1^s.

No. 181 (DUN 181AB). Quadrant corrected from nf to np. *2nd outlier* in Quadrant corrected PA with respect to the whole catalogue. Also |ΔSep| > *Mean Sep*. Dunlop's uncorrected *Mean PA* = 65°. Dunlop's corrected PA = 295°. *Gaia DR2* precessed PA ∼347.5°. Perhaps Dunlop's *Angle of Pos* should be 75° 0′ and not 25° 0′. *Mean Sep* = 9″, *Gaia DR2* precessed Sep ∼ 29.2″.

No. 183∗ (DUN 183AB). *2nd outlier* in Sep. Also |ΔSep| > *Mean Sep*. Component A is k Lup, and component B is HD 137059. Dunlop's Sep = 12″, the Sep from precessed *Gaia DR2* is ∼89.8″. There is a second Dunlop *Distance*, 15″ as Dunlop marked this as 'Three stars in a line'. Unable to explain discrepancy.

No. 186 (DUN 186). Quadrant corrected from sf to np. Dunlop uncorrected *Mean PA* is ∼125.0°. Dunlop corrected *Mean PA* is ∼305.0°. Precessed *Gaia DR2* PA is ∼296.7°. ASCC and *Gaia DR2* source identifiers of components in Letchford et al. (2019b,c) swapped.

No. 187 (DUN 187). Also |ΔSep| > *Mean Sep*. *Mean Sep* = 10″, *Gaia DR2* precessed Sep ∼ 33.7″.

No. 188 (DUN 188). Quadrant corrected from sf to sp. Dunlop uncorrected *Mean PA* is ∼150°. Dunlop corrected *Mean PA* is ∼210.0°. Precessed *Gaia DR2* PA is ∼215.6°.

No. 190 (DUN 190AB). Quadrant corrected from nf to sf. Also |ΔSep| > *Mean Sep*. Dunlop uncorrected *Mean PA* is ∼85.0°. Dunlop corrected *Mean PA* is ∼95.0°. Precessed *Gaia DR2* PA is ∼90.4°. *Mean Sep* = 3″, *Gaia DR2* precessed Sep ∼ 6.5″.

No. 192 (DUN 192 AB,C). Quadrant corrected from nf to sf. Dunlop uncorrected *Mean PA* is ∼50.0°. Dunlop corrected *Mean PA* is ∼130.0°. Processed *Gaia DR2* PA is ∼145.9°.

No. 194 (DUN 194AC). Quadrant corrected from np to nf. Also |ΔSep| > *Mean Sep*. Dunlop uncorrected *Mean PA* is ∼317.0°. Dunlop corrected *Mean PA* is ∼43.0°. Precessed *Gaia DR2* PA is ∼49.1°. *Mean Sep* = 10″, *Gaia DR2* precessed Sep ∼ 45.2″.

No. 195 (DUN 195AB). Also |ΔSep| > *Mean Sep*. *Mean Sep* = 5″, *Gaia DR2* precessed Sep ∼ 11.8″.

No. 197∗ (RMK 21AC). *2nd outlier* in Sep. Also |ΔSep| > *Mean Sep*. Component A is η Lup, and component B is CD-3810797B. Dunlop's *Mean Sep* ∼50.4″, and the precessed *Gaia DR2* Sep is ∼115.4″. Unable to explain discrepancy.

No. 198 (two). *Gaia DR2* precessed Quadrant is sp. Also |ΔSep| > *Mean Sep*. Dunlop *Mean PA* remains 180.0°. Precessed *Gaia DR2* PA is ∼192.0°. *Mean Sep* = 30″, *Gaia DR2* precessed Sep ∼ 81.3″.

No. 199 (DUN 199AC). Also |ΔSep| > *Mean Sep*. *Mean Sep* = 12″, *Gaia DR2* precessed Sep ∼ 43.6″.

No. 200 (DUN 200). Quadrant corrected from sf to sp. Also |ΔSep| > *Mean Sep*. Dunlop uncorrected *Mean PA* is ∼172.0°. Dunlop corrected *Mean PA* is ∼188.0°. Precessed *Gaia DR2* PA is ∼197.4°. *Mean Sep* = 17″, *Gaia DR2* precessed Sep ∼ 41.9″.

No. 202 (DUN 202AC). Also |ΔSep| > *Mean Sep*. *Mean Sep* = 26″, *Gaia DR2* precessed Sep ∼ 57.9″.

No. 208 (one). Nearest suitable double star from the forward precessed Dunlop position is DUN 211BC at a distance of ∼2930″.

No. 209 (DUN 209AB). Quadrant corrected from sp to sf. Dunlop uncorrected *Mean PA* is ∼210.0°. Dunlop corrected *Mean PA* is ∼150.0°. Precessed *Gaia DR2* PA is ∼146.4°.

No. 211 (DUN 211BC). Quadrant corrected from np to sp. Also |ΔSep| > *Mean Sep*. Dunlop uncorrected *Mean PA* is ∼330.0°. Dunlop corrected *Mean PA* is ∼210.0°. Precessed *Gaia DR2* PA is ∼194.2°. *Mean Sep* = 20″, *Gaia DR2* precessed Sep ∼ 45.1″.

No. 212 (DUN 212AB). Quadrant corrected from sp to np. Also |ΔSep| > *Mean Sep*. Dunlop uncorrected *Mean PA* is ∼228.0°. Dunlop corrected *Mean PA* is ∼312.0°. Precessed *Gaia DR2* PA is ∼286.4°. *Mean Sep* = 5″, *Gaia DR2* precessed Sep ∼ 16.2″. Perhaps Dunlop's Distance (column 7) should be 15″.

No. 215 (DUN 215AB). Also |ΔSep| > *Mean Sep*. *Mean Sep* = 15″, *Gaia DR2* precessed Sep ∼ 54.8″.

No. 216∗ (DUN 216AC). Quadrant corrected from nf to np. *2nd outlier* in Sep. Also |ΔSep| > *Mean Sep*. Dunlop uncorrected *Mean PA* is ∼30.0°. Dunlop corrected *Mean PA* is ∼330.0°. Precessed *Gaia DR2* PA is ∼313.3°. Dunlop's *Mean Sep* is ∼30.0″, the precessed *Gaia DR2* Sep is ∼103.3. Unable to explain discrepancy.

No. 221 (DUN 211). *Gaia DR2* precessed Quadrant is sf. Dunlop *Mean PA* remains 180.0°.

No. 224 (DUN 224AC). Quadrant corrected from sf to nf. Dunlop uncorrected *Mean PA* is ∼115.6°. Dunlop corrected *Mean PA* is ∼64.4°. Precessed *Gaia DR2* PA is ∼63.7°.

No. 230 (DUN 230). *1st outlier* in Sep. Component A is HD 192724A, component B is HD 192724B. Dunlop's Sep (by only one method) is ∼65.6″, *Gaia DR2* precessed Sep is ∼10.15″. Neither star is noted as a high proper motion star in SIMBAD. Unable to explain discrepancy.

No. 231∗ (DUN 231). *1st outlier* in RA. Component A is HD 195459. Dunlop's RA is $20^{h}\ 16^{m}\ 28^{s}$, *Gaia DR2* precessed RA is $20^{h}\ 18^{m}\ 27^{s}$. Probably a typographical error. Dunlop's 16^{m} should be 18^{m}.

No. 232∗ (DUN 232). *1st outlier* in DE. Component A is mu.02 Oct. Dunlop's DE is −76° 56′, *Gaia DR2* precessed DE is −75° 56′ 15.72″. Could be due to a typographical error, as in should be −75° instead of −76°. In the WDS as 20417-7521 DUN 232.

No. 235∗ (DUN 235AC). Quadrant corrected from sp to sf. Dunlop uncorrected *Mean PA* is ∼236.6°. Dunlop corrected *Mean PA* is ∼123.4°. Precessed *Gaia DR2* PA is ∼124.3°.

No. 238 (DUN 238AB). *Gaia DR2* precessed Quadrant is nf. Dunlop *Mean PA* remains 90°.

No. 242∗ (H 6 119AB). *1st outlier* in Δ *Declin* (column 9). Δ *Declin* is 37.50″. The calculated Δ*Declin* [calculated from the *Mean PA*, *Mean Sep*, and declination (column 4)] is ∼75.6″. Perhaps a typographical error (as in 37 instead of 73).

No. 245 (DUN 245). *2nd outlier* in vB – vA with respect to the whole catalogue. Component A is HD 218392 (high proper motion star) and component B is CPD-60 7635B (high proper motion star). Dunlop's vA = 7 and vB = 13. *Gaia DR2* calculated vA is ∼7.35 and calculated vB is ∼9.79.

No. 251∗ (DUN 251). *Gaia DR2* precessed Quadrant is np. Dunlop PA remains 270°, *Gaia DR2* precessed PA is 291.4°.

No. 252∗ (two). Quadrant corrected from sf to nf. *1st outlier* in corrected PA. Dunlop uncorrected *Mean PA* is ∼117.4°. Dunlop corrected *Mean PA* is ∼62.6°. Precessed *Gaia DR2* PA is ∼8.0°. Dunlop's *Angle of Pos* is also wrong. Incorrect discoverer code (DisC) and components (Comp) in Letchford et al. (2019b,c).

No. 253∗ (LAL 192). Listed in the WDS as 14067-3622, but is identified here as LAL 192, WDS 23544-2703. *2nd outlier* in DE. Dunlop *Quadrant* is simply p, hence the uncorrected *Mean PA* = 270°. The *Gaia DR2* Quadrant for the secondary of LAL 192 is sp (*Gaia DR2* precessed PA ∼266.3°), but the corrected *Mean PA* remains 270°, since there is no other information to construct a more precise *Mean PA*. Component A of LAL 192 is HD 223991A. Dunlop's RA is $23^{h}\ 46^{m}\ 0^{s}$, DE is −28° 26′ and the *Gaia DR2* precessed RA is $23^{h}\ 45^{m}\ 22^{s}$ and the precessed DE is ∼−28° 00′ 43″.

APPENDIX B: METHOD OF DETERMINING DUNLOP'S *Mean PA* AND *Mean Sep*

No. 18∗ has relevant information in all necessary columns (4–9) to serve as an example of each of the four ways of determining Dunlop's position angle for that double star.

(i) **PA method i** *Angle of Pos* (Column 5) = 30° 4′, *Quadrant* (Column 6) = nf. Therefore,

PA = 90° – 30° 4′ = 59° 56′ ≈ 59.93°

(ii) **PA method ii** *Declination* (Column 4) = −53° 46′, *Quadrant* (Column 6) = nf, Δ*AR* (Column 8) = 1ˢ.137, Δ*Declin* (Column 9) = 6.659″. Therefore,

$\Delta\mathrm{RA} = 15\cos(-53^\circ\ 46')1.137 \approx 10.08''$

$\mathit{Angle\ of\ Pos} = \arctan(\Delta \mathit{Declin}/\Delta\mathrm{RA})180/\pi \approx 33.45^\circ$

PA ≈ 90° – 33.45° ≈ 56.55°

(iii) **PA method iii** *Declination* (Column 4) = −53° 46′, *Quadrant* (Column 6) = nf, *Distance* (Column 7) = 12.547″, Δ*AR* (Column 8) = 1ˢ.137. Therefore,

$\Delta\mathrm{RA} = 15\cos(-53^\circ\ 46')1.137 \approx 10.08''$

$\mathit{Angle\ of\ Pos} = \arccos(\Delta\mathrm{RA}/\mathit{Distance})180/\pi \approx 36.55^\circ$

PA ≈ 90° – 36.55° ≈ 53.45°

(iv) **PA method iv** *Declination* (Column 4) = −53° 46′, *Quadrant* (Column 6) = nf, *Distance* (Column 7) = 12.547″, Δ*Declin* (Column 9) = 6.659″. Therefore,

$\Delta\mathrm{RA} = 15\cos(-53^\circ\ 46')1.137 \approx 10.08''$

$\mathit{Angle\ of\ Pos} = \arcsin(\Delta \mathit{Declin}/\mathit{Distance})\ 180/\pi \approx 32.05^\circ$

PA ≈ 90° – 32.05° ≈ 57.95°

The *Mean PA* for No. 18∗ is then 57.0°.

(i) **Sep method i** *Distance* (Column 7) = 12.547″. Therefore, Sep = 12.547″

(ii) **Sep method ii** *Declination* (Column 4) = −53° 46′, Δ*AR* (Column 8) = 1.137ˢ, Δ*Declin* (Column 9) = 6.659″. Therefore,

$\Delta\mathrm{RA} = 15\cos(-53^\circ\ 46')1.137 \approx 10.08''$

$\mathrm{Sep} = \sqrt{(\Delta AR^2 + \Delta Declin^2)} \approx 12.082$ arcsec

(iii) **Sep method iii** *Declination* (Column 4) = −53° 46′, *Angle of Pos* (Column 5) = 30° 4′, Δ*AR* (Column 8) = 1.137ˢ. Therefore,

$\Delta\mathrm{RA} = 15\cos(-53^\circ\ 46')1.137 \approx 10.08''$

Sep = ΔRA/cos(*Angle of Pos*) ≈ 11.648″

(iv) **Sep method iv** *Angle of Pos* (Column 5) = 30° 4′, Δ*Declin* (Column 9) = 6.659″. Therefore,

Sep = Δ*Declin*/sin(*Angle of Pos*) ≈ 13.291″.

The *Mean Sep* for No. 18∗ is then 12.4″.

APPENDIX C: DUNLOP DOUBLE STARS THAT FALL WITHIN CONTEMPORARY 1820S ACCURACY LIMITS

Table C1 list the Dunlop double stars from the *Dunlop Catalogue* that fall within contemporary 1820s accuracy limits for the given parameter. See Section 3.4 for the description of these contemporary astrometric and photometric standards.

Table C1. Dunlop double stars that fall within the contemporary 1820s accuracy limits given in column 1. For the meaning of Δ, see equations (1) and (2).

Measure range	***Banks Refractor***	***Dunlop Reflector***
$-5'' < \Delta\mathrm{RA} < +5''$	102∗ = 103∗	None
$-5'' < \Delta\mathrm{DE} < +5''$	42∗, 109∗, 116∗, 149∗	60, 67, 172, 175, 188, 204, 221, 247
$-4^\circ < \Delta\mathrm{PA} < +4^\circ$ (Quadrant corrected)	4∗, 26∗, 27∗, 28∗, 29∗, 31∗, 38∗, 40∗, 43∗, 52∗, 62∗, 73∗, 76∗, 88∗, 95∗, 99∗, 102∗, 103∗, 112∗, 113∗, 116∗, 117∗, 119∗, 126∗, 129∗, 131∗, 133∗, 146∗, 153∗, 163∗, 169∗, 176∗, 179∗, 182∗, 196∗, 197∗, 229∗, 231∗, 232∗, 235∗, 236∗, 241∗, 249∗, 250∗	59, 68, 71, 72, 114, 128, 150, 168, 195, 207, 209, 219, 224, 247
$-0.5'' < \Delta\mathrm{Sep} < +0.5''$	28∗, 29∗, 39∗, 66∗, 74∗, 111∗, 148∗, 149∗, 249∗	213
$-0.3 < \Delta\mathrm{VmagA} < +0.3$	6∗, 19∗, 20∗, 26∗, 39∗, 56∗, 62∗, 76∗, 78∗, 113∗, 119∗, 146∗, 163∗, 174∗, 241∗, 242∗	23, 58, 60, 61, 68, 71, 72, 80, 81, 82, 85, 101, 110, 115, 118, 135, 144, 157, 162, 171, 187, 192, 193, 203, 208, 212, 213, 215, 224, 225, 234, 237
$-0.3 < \Delta\mathrm{VmagB} < +0.3$	16∗, 17∗, 20∗, 26∗, 28∗, 32∗, 36∗, 38∗, 39∗, 73∗, 74∗, 86∗, 103∗, 109∗, 111∗, 116∗, 142∗, 143∗, 164∗, 197∗, 216∗, 229∗, 231∗	14, 57, 58, 67, 68, 81, 168, 175, 191, 195, 203, 212, 219, 224, 239, 247

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