Measures of Ten Sco Doubles and the Determination of Two Orbits

Matthew James[1], Meg Emery[2], Graeme L. White[3], Roderick Letchford[4], Stephen Bosi[5]

1. University of New England, Armidale, NSW, Australia; m.b.james27@gmail.com
2. Kildare Catholic College, Wagga Wagga, NSW, Australia; megcolemery@gmail.com
3. Centre for Astronomy, University of Southern Queensland, Toowoomba, QLD, Australia; graemewhiteau@gmail.com
4. Vianney College Seminary, Wagga Wagga, NSW, Australia; rodvianney@yahoo.com.au
5. University of New England, Armidale, NSW, Australia; sbosi@une.edu.au

Abstract: We present measures for 10 pairs in the constellation of Scorpius using a C14 telescope, Lucky Imaging, and the Reduc software. The separations of Alpha Centauri AB, as determined from the orbital elements of Pourbaix and Boffin (2016), were used as an image scale and position angle calibrator.

Our internal uncertainties are ~0.06 arcsec in r and ~0.06 degree in PA. There is excellent agreement with historic data extrapolated to epoch of observation (~2018.53), and micro-arcsecond positions from the GAIA database where the differences are ~0.05 arcsec in r and ~0.15 degrees in PA.

In addition, we present rectilinear elements for the 10 Sco pairs and orbital elements for two of them. Ephemera are given for these pairs based on both the rectilinear elements and the orbital elements.

1. Introduction

We present here the first of two papers that explore the limits of uncertainty that can be obtained using different techniques to determine standard separation, ρ, and position angles, PA. In this first paper we undertake lucky imaging measures of 10 pairs in the constellation of Scorpio (Sco) using drifting images, with the image scale and the camera's position angle calibrated against an accurate ephemeris of Alpha Centauri. A second paper (James *et al.,* in preparation for journal submission) will undertake a more detailed analysis of the accuracy of different applications of lucky imaging.

We present measures for these pairs and look for uncertainty through comparison with extrapolations of historic data and micro-arcsecond positions from the Gaia DR2 database. One method to determine if a double star system is a visual double or a binary system is to observe the relative motions between the primary and secondary component over a period of time. The trend can be used to differentiate between orbital or rectilinear motion. Section 5 looks at the motion of the pairs over time utilising the historic record, and Section 6 determines the rectilinear motion of the pairs following the method of Letchford, White and Ernest (2018a). For binary systems with very short orbital arcs the method developed by Letchford, White and Ernest (2018b) is used in Section 7 to determine grade 5 orbits for two of the pairs in this study.

2. Selection of Pairs.

The objects in this study were chosen from the Carro Double Star Catalogue (Carro, 2013) that have a separation, ρ, larger than 4 arcseconds; a limit imposed by local seeing conditions.

The constellation Scorpius was specifically chosen since the constellation was near zenith at the time of observation. High elevations reduce the effects of airmass and give better video captures.

Table 1 lists the stars that make up the 10 pairs. Here the WDS designation is given along with the WDS Discovery Code (*Disc*). Both are adapted from the Washington Double Star Catalog (WDS, Mason, *et al.,* 2001). The names/identifiers of the stars are from the SIMBAD database (Wegner, *et al.,* 2000), the ASCC database (Kharchenko, 2001) and from the DR2 release (Brown, *et al.*, 2018) of the GAIA astrometric mission (Prusti, *et al.*, 2016).

3. Observations

Equipment and Software.

The telescope used to make the observations is the

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Table 1. Modern Identifications of the Stars that make up the 10 Sco Pairs

	WDS	Disc	SIMBAD	ASCC	GAIA
1	16029-2501	BU 38A,B	TYC 6784-1420-1	1683158	6235913255305953536
			TYC 6784-1425-1	1683157	6235913255305954432
2	16095-3239	BSO 11A,B	HD 144927	1778073	6035755719057732224
			TYC 7334-2610-1	1778075	6035755719057730816
3	16143-1025	STF2019AB,C	HD 145996	1401854	4344884406644977280
			BD-10 4276C	1401855	4344884406644973952
4	16195-3054	BSO 12A,B	HD 146836	1778791	6037514800199297152
			HD 146835	1778788	6037514800213601024
5	16201-2003	SHJ 225A,B	V* V933 Sco	1587367	6244725050721030528
			HD 147009	1587364	6244725905417556992
6	16247-2942	H N 39A,B	HD147723	1684185	6038073970589665280
			HD 147722	1684184	6038073970589665536
7	16482-3653	DUN 209A,B	HD 151315	1875678	5971596329361239808
			HD 151316	1875680	5971596260664472704
8	16510-3731	HJ 4889A,B	HD 151771A	1875852	5971527094516942720
			HD 151771B	1875854	5971527094516943488
9	17290-4358	DUN 217A,B	HD 158042	1978893	5958561447264080768
			CD-43 11741B	1978895	5958561447264078208
10	17512-3033	PZ 5A,B	HD 162220	1788279	4056340704108946176
			CD-30 14802B	1788278	4056340704108937600

Bill Webster 14-inch Celestron Schmidt-Cassegrain Telescope located at the Kirby Observatory of the University of New England, Armidale, NSW, Australia. See Figure 1. The telescope is equipped with a flip-mirror box which allows the user to switch between the camera and eyepiece. The camera, a ZWO ASI120MM-S USB 3.0 Monochrome CMOS, was used for its image resolution, temporal resolution, and the USB 3.0 download bandwidth. A red (approximating R) filter was used to reduce the effects of atmospheric distortion on the video captures.

Figure 1. The Kirby Observatory of the University of New England, Armidale, NSW, Australia. The dome covers the Bill Webster 14-inch Celestron Schmidt-Cassegrain Telescope used in this study.

The video capture software used was SharpCaps version 3.1, and the analysis software used was Reduc version 5.36, provided by Florent Losse. Reduc allows for the rapid disposal of data (capture frames) resulting in a text file output of the X and Y coordinates of the primary and secondary star on the chip, which were used in Microsoft Excel 2016 to calculate the PA and ρ along with their formal uncertainties.

Lucky Imaging

The lucky imaging technique is utilized which is akin to high speed photography; high frame-rate and low exposure times. When used on astronomical objects, like double stars, the short exposure time (<100 ms) has the effect of freezing the perturbed atmosphere, reducing image distortion and increasing the chance of obtaining higher quality images (Fried, 1977).

Video Drift Method.

Observations were made using the video drift method outlined by Nugent (2011). In brief, the pair is placed to the east side just outside of the video frame, the telescope's drive motor is deactivated and the video

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capture is then started, which results in the image of the pair drifting across the field of view of the camera (and out of the west side of the camera frame).

Calibration – Image Scale and Position Angle.

Calibration of the image scale and position angle was undertaken using the prominent southern hemisphere pair Alpha Centauri (α Cen). α Cen has been extensively studied (see White, Letchford and Ernest, 2018) over ~260 years and ~3.5 orbits. Precise orbital elements by Pourbaix and Boffin (2016) are available in the WDS Sixth Orbit Catalog, and these give precise predicted ρ and PA for the pair at the epoch of observation. Concurrent observations of α Cen underpin the calibration of the Sco measures presented here, and uncertainties in the calibration observations of α Cen contribute to the uncertainties in the measures presented below.

Analysis.

For each Sco pair, 5 AVI format video captures were taken using the video drift method. Each video capture was then reduced using all frames with ρ or PA outside of 2 standard deviations from the mean being removed. Further reduction was undertaken using Excel. Further details of the data analysis are given by James (2019).

Image Scale for the Calibration of Separation.

To determine the ρ for the 10 Sco pairs, a pixel per arcsecond ratio was calculated for the C14/ZWO ASI120MM-S telescope/camera based on the observations of α Cen; the image scale, $R_{px/as}$, was determined to be 5.664 pixels per arcsecond. Again further details of the data analysis are given in James (2019).

Position Angle.

The position angle was computed from the drift angle of the individual stars across the chip of the camera, the individual positions on each frame having been determined using Reduc. Again further details are given by James (2019).

$$SEM = \bar{M}\sqrt{\left(\frac{\sigma_M}{\bar{M}\sqrt{N_M}}\right)^2 + \left(\frac{\sigma_{cal}}{M_{cal}\sqrt{N_{cal}}}\right)^2}$$

Equation 1. The equation used to calculate the standard error in the mean for PA and ρ

4. Measures

The measures for the 10 Sco objects observed are given in Table 2. The formal uncertainties in these measures are the uncertainty of the observations of the Sco pairs combined with the uncertainty in the calibration observations of α Cen (for the ρ). These uncertainties are the Standard Error in the Mean (SEM) of 5 independent observations.

Equation 1 was used to calculate the Standard Error in the Mean (SEM) uncertainty of the measures. This equation combines both the uncertainty in the observations and in the calibrator into a single SEM uncertainty. Here N is the number of observations of a particular pair; always $N = 5$ for this paper. is the average measure (either PA or ρ) of the N number of observations. *cal* refers to the calibrator, i.e. α Cen. σ is the standard deviation (SD) of the measures of N observations.

5. Historic Observations.

Historic positional measures have been obtained from the supplementary catalogues of the WDS. For the 10 pairs studied here, there are a total of 420 observations starting as early as 1783.23 (for the pair WDS 16201-2003).

Table 2. Measures at Epoch for 10 Sco Pairs.

	WDS	Disc	Epoch	Sep (arcsec)	SEM (arcsec)	PA (deg)	SEM(deg)
1	16029-2501	BU 38	2018.542	4.472	0.023	343.091	0.280
2	16095-3239	BSO 11 AB	2018.526	7.636	0.033	83.610	0.024
3	16143-1025	STF2019 AB,C	2018.542	22.320	0.100	153.021	0.094
4	16195-3054	BSO 12 AB	2018.523	23.579	0.098	317.976	0.024
5	16201-2003	SHJ 225	2018.542	46.686	0.194	332.601	0.021
6	16247-2942	H N 39	2018.526	3.999	0.017	359.241	0.047
7	16482-3653	DUN 209AB	2018.545	23.914	0.100	137.972	0.034
8	16510-3731	HJ 4889	2018.526	6.761	0.028	4.224	0.058
9	17290-4358	DUN 217	2018.526	13.457	0.056	167.837	0.022
10	17512-3033	PZ 5 AB	2018.526	10.101	0.043	189.323	0.049

Table 3. Linear fits Coefficient to the Historic Data for 10 Sco Pairs.

	WDS	Disc	Rho			PA		
			A	B	R^2	C	D	R^2
1	16029-2501	BU 38	0.00126	1.965	0.061	-0.0605	465.907	0.896
2	16095-3239	BSO 11 AB	-0.00448	16.606	0.118	-0.0148	113.872	0.300
3	16143-1025	STF2019 AB,C	0.00908	4.589	0.316	0.0032	147.704	0.014
4	16195-3054	BSO 12 AB	-0.00432	31.821	0.057	-0.0147	347.660	0.213
5	16201-2003	SHJ 225	-0.00124	49.204	0.033	-0.0027	338.412	0.067
6	16247-2942	H N 39	-0.01886	42.323	0.859	0.0503	256.409	0.617
7	16482-3653	DUN 209AB	0.00177	20.041	0.033	-0.0563	251.380	0.937
8	16510-3731	HJ 4889	-0.00144	9.612	0.056	-0.0090	22.915	0.201
9	17290-4358	DUN 217	-0.00449	22.343	0.375	-0.0065	181.831	0.043
10	17512-3033	PZ 5 AB	0.00023	9.671	0.002	-0.0017	192.841	0.027

Appendix 1 presents the ρ and PA for the 10 Sco pairs. Datapoints as orange squares were deemed to be outliers and rejected based on a subjective assessment of the trend. The green triangle datapoints are the measures from this work (taken from Table 2).

Precession of Position Angles.

All plots in Appendix 1 are for PA (and ρ) at the epoch and equinox of observation. The correction of the PA to bring them to a standard Equinox (say J2000) have not been applied. This precessional rotation of the frame is defined in Aitken (1935, p. 73) and Argyle (2004). As all pairs in the study are in close proximity (~16h 30m, -20^o) the PA precession of each pair is approximately 0.55 degree per century in the sense that the PA is decreasing with time. A much smaller component of PA precession based on the proper motion of the primary star (Argyle, 2004) was ignored in this work, except for those in Appendices 2 & 3, Tables 6, 7, & 9.

Uncertainties in Historic Measures.

White, Letchford and Ernest (2018) have shown that the precision of historic observations of double stars has improved with epoch; from ~0.6 arcseconds to ~0.14 arcseconds in ρ, and ~0.74 degree to ~0.5 degree in PA, over our period of interest (~1800 to the present). This trend towards better quality data is also visible here as it is seen that the spread of data points around the trend line converges with increasing time.

Fitted Trend Lines.

Each plot in Appendix 1 has been fitted by an unweighted linear trend line and the fitted parameters are given in Table 3 along with the derived correlation coefficient, R^2.

For the fit to the separation, ρ, with Epoch plot, the fit is defined as

$$\text{Separation, } \rho = A \times Epoch + B$$

and the fitted trend line for the Position Angle, PA, is

$$\text{Position Angle, } PA = C \times Epoch + D$$

The fitted parameters *A*, *B*, *C* and *D* are presented in Table 3 along with the fitted correlation coefficient, R^2.

6. Accuracy of the 10 Sco Measures.

The measures for the 10 Sco pairs in Table 2 were now compared with two external measures (*i*) the historic measures extrapolated to the epoch of observation, and (*ii*) the position given in the Gaia DR2 catalogue which was precessed to the epoch of observation.

Using a fitted linear trendline extrapolated from the historic measures from Table 3, ρ and PA are calculated for the epoch of observations and shown in Table 4 in column History.

The ρ and PA for the pairs obtained at epoch from the Gaia DR2 data base are given in Table 4 under heading GAIA.

The differences between the measures reported here (shown here as This Paper, TP) and those extrapolated from the historic data (shown as Hist) and the Gaia database are given in Table 5. Here units for differences in ρ are arcsecond, and degrees in PA respectively. There is excellent agreement between the measures of historic and Gaia values. The mean offset between the data sets (shown as Average =), and its formal uncertainty (shown as SEM =) are all self-consistent and consistent with the formal uncertainties quoted for the measures in Table 2. The average SEM in the offset of ρ is 0.04 arcseconds, and the average SEM in the offset

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Table 4. Comparison of Measures with (i) Extrapolated Historic Data and (ii) GAIA positions and Proper Motions.

	WDS	Disc	Rho			PA		
			This Work (arcsec)	History (arcsec)	GAIA (arcsec)	This Work (deg)	History (deg)	GAIA (deg)
1	16029-2501	BU 38	4.472	4.504	4.487	343.091	343.759	343.445
2	16095-3239	BSO 11 AB	7.636	7.571	7.649	83.610	83.947	83.644
3	16143-1025	STF2019 AB,C	22.320	22.924	21.625	153.021	154.089	155.359
4	16195-3054	BSO 12 AB	23.579	23.109	23.498	317.976	318.046	318.180
5	16201-2003	SHJ 225	46.686	46.703	46.637	332.601	332.982	332.707
6	16247-2942	H N 39	3.999	4.257	4.006	359.241	357.977	359.322
7	16482-3653	DUN 209 AB	23.914	23.616	23.888	137.972	137.740	138.120
8	16510-3731	HJ 4889	6.761	6.711	6.767	4.224	4.805	4.503
9	17290-4358	DUN 217	13.457	13.278	13.433	167.837	168.680	168.040
10	17512-3033	PZ 5 AB	10.101	10.136	10.110	189.323	189.498	189.580

Table 5. Differences of Measures with (i) Extrapolated Historic Data and (ii) GAIA positions and Proper Motions.

WDS	Disc	Diff Rho	Diff PA	Diff Rho	Diff PA	Diff Rho	Diff PA
		GAIA - TP	GAIA - TP	Hist - TP	Hist - TP	Hist - GAIA	Hist - GAIA
16029-2501	BU 38	0.015	0.353	0.032	0.668	0.017	0.314
16095-3239	BSO 11 AB	0.012	0.034	-0.065	0.337	-0.077	0.303
16143-1025	STF2019 AB,C						
16195-3054	BSO 12 AB	-0.081	0.204	-0.470	0.071	-0.389	-0.134
16201-2003	SHJ 225	-0.050	0.106	0.017	0.380	0.066	0.274
16247-2942	H N 39	0.007	0.080	0.258	-1.264	0.252	-1.344
16482-3653	DUN 209 AB	-0.027	0.148	-0.299	-0.232	-0.272	-0.379
16510-3731	HJ 4889	0.006	0.279	-0.050	0.582	-0.056	0.303
17290-4358	DUN 217	-0.024	0.202	-0.179	0.843	-0.155	0.640
17512-3033	PZ 5 AB	0.009	0.257	0.035	0.175	0.026	-0.082
	Average =	-0.015	0.185	-0.080	0.173	-0.065	-0.012
	SEM =	0.011	0.034	0.071	0.210	0.063	0.195

of PA is 0.12 degrees.

This comparison does not extend to WDS 16143-1025. The brightest (primary) component observed in this work is WDS 16143-1025 AB, a very close pair separated by only 0.2 arcseconds. The positions, and proper motions, reported for components AC by both the HIPPARCOS and GAIA mission are inconsistent and no comparison has been made with the measures reported in Table 2.

7. Rectilinear Motion.

The motion of the components of a double star may be characterised as a rectilinear motion of the secondary relative to the primary star. Rectilinear motion is usually visualized as a straight line on a Cartesian plot where the primary star is the origin (0,0) position.

Such descriptions are an important tool in distinguishing between optical doubles and physical binaries since it is the variations from linearity that allows a sensitive identification of a Keplerian system.

As stated above, White, Letchford and Ernest (2018) have shown the precision of historic observations of double stars to be ~0.14 arcsec in ρ, and ~0.5 degree in PA, at best, for recent measures, and where

(Text continues on page 495)

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Table 6. Rectilinear Elements for 10 Sco pairs.

	WDS	x0 (DE0)	xa	y0(RA0)	ya	t0	theta0	rho0	xb	yb	move	x-inter	y-inter
		+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-		
1	16029-2501	3.58	-32	-2.35	-0.0050	2200	326.7	4.28	10.9	8.8	5.9	5.12	-7.81
		0.02	0.0001	0.07	0.0003	200	0.8	0.04	0.2	0.6	0.2		
2	16095-3239	4.23	0.001079	3.6	-0.00127	5000	40.0	5.6	-1.34	10.2	1.67	7.28	8.59
		0.07	2.23E-05	0.5	0.00014	900	4.0	0.3	0.04	0.3	0.11		
3	16143-1025	-14	-0.005	15.4	-0.004	700	133.0	21	-11	19	6.2	-30.80	28.60
		2	0.002	2.5	0.002	1400	7.0	2	4	4	1.3		
4	16195-3054	9	0.0026	4	-0.0062	-1000	23.0	10	12	-3	6.7	10.99	26.16
		4	0.0012	4	0.0012	700	20.0	4	2	3	1.1		
5	16201-2003	3	-0.00115	-25.7	-0.00013	35000	276.0	25.8	43.80	-21	1.156	230.98	-25.98
		1	3.07E-05	1.5	4.33E-05	2000	2.0	1.5	0.06	0.09	0.004		
6	16247-2942	0.598	-0.02345	1.30	0.0090	2170	69.1	1.40	51.35	-18	25.11	3.91	1.49
		0.002	1.44E-05	0.02	0.0015	11	0.3	0.02	0.03	0.3	0.05		
7	16482-3653	-20.2	0.0038	4.0	0.0191	1390	168.8	20.6	-25.4	-22.5	19.4	-20.99	106.08
		0.3	0.0005	0.3	0.0005	90	0.8	0.3	0.9	0.9	0.4		
8	16510-3731	6.2	-3.40E-05	-2	-0.0001	17000	350.0	6.4	6.81	0.8	0.1	6.60	-26.89
		0.5	3.37E-05	4	0.0003	7000	40.0	1.1	0.07	0.6	0.3		
9	17290-4358	-6.9	-0.00032	-5	0.0004	-17000	220.0	9	-12.51	1.9	0.5	-11.03	-14.30
		1.8	8.98E-05	6	0.000303	17000	30.0	4	0.18	0.6	0.5		
10	17512-3033	-9.0	-0.00027	2.2	-0.001	-1500	170.0	9.3	-9.43	0.5	1.1	-9.55	39.47
		0.3	8.30E-05	1.2	0.004	1200	7.0	0.4	0.17	0.7	0.3		

Table 7. Ephemeris for the10 Sco Pairs based on the Rectilinear Motion.

	WDS	1991.25 PA°	1991.25 Sep"	2015.5 PA°	2015.5 Sep"	2020.0 PA°	2020.0 Sep"	2025.0 PA°	2025.0 Sep"	2030.0 PA°	2030.0 Sep"	2035.0 PA°	2035.0 Sep"	2040.0 PA°	2040.0 Sep"
		+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
1	16029-2501	345.59	4.53	343.85	4.48	343.52	4.47	343.15	4.46	342.79	4.46	342.42	4.45	342.05	4.44
		0.09	0.00	0.00	0.00	0.02	0.00	0.04	0.00	0.05	0.00	0.07	0.00	0.09	0.00
2	16095-3239	83.99	7.68	83.77	7.65	83.73	7.65	83.69	7.64	83.64	7.64	83.60	7.63	83.55	7.62
		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
3	16143-1025	152.81	22.29	153.18	22.35	153.24	22.36	153.32	22.37	153.39	22.38	153.47	22.39	153.54	22.40
		0.12	0.05	0.00	0.00	0.03	0.01	0.05	0.02	0.08	0.03	0.10	0.04	0.13	0.05
4	16195-3054	318.52	23.32	318.35	23.46	318.32	23.49	318.28	23.52	318.25	23.55	318.21	23.58	318.18	23.61
		0.07	0.03	0.00	0.00	0.02	0.01	0.03	0.01	0.04	0.02	0.06	0.02	0.07	0.03
5	16201-2003	332.83	46.66	332.81	46.64	332.81	46.63	332.80	46.63	332.80	46.62	332.79	46.62	332.79	46.62
		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	16247-2942	356.55	4.65	359.13	4.07	359.69	3.97	0.35	3.85	1.05	3.73	1.79	3.62	2.58	3.50
		0.04	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.03	0.00	0.05	0.00	0.06	0.00
7	16482-3653	139.32	23.65	138.33	23.89	138.15	23.93	137.95	23.98	137.75	24.03	137.56	24.08	137.36	24.13
		0.03	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.02	0.01	0.02	0.01	0.03	0.01
8	16510-3731	4.66	6.76	4.63	6.76	4.63	6.76	4.62	6.76	4.62	6.76	4.61	6.76	4.60	6.76
		0.06	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.04	0.00	0.05	0.00	0.06	0.00
9	17290-4358	168.22	13.43	168.18	13.44	168.18	13.44	168.17	13.44	168.16	13.45	168.16	13.45	168.15	13.45
		0.03	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.02	0.00	0.03	0.00	0.03	0.00
10	17512-3033	189.58	10.10	189.72	10.11	189.75	10.12	189.78	10.12	189.81	10.12	189.84	10.12	189.87	10.12
		0.05	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.03	0.00	0.04	0.00	0.05	0.00

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Table 8. Orbital Elements for 2 Sco pairs.

	WDS	P yrs	a "	I °	Ω °	T yr	e	ω °
		+/-	+/-	+/-	+/-	+/-	+/-	+/-
2	16095-3239	150000	40	100.0	120	-11000	0.52	350
		20000	4	2.3	7	15000	0.02	115
4	16195-3054	33000	34	118.0	110	-1900	0.76	351
		5000	4	1.2	10	100	0.09	20

Table 9. Ephemeris for the 2 Sco Pairs based on the Orbital Motion.

	WDS	1991.25 PA°	1991.25 Sep"	2015.5 PA°	2015.5 Sep"	2020.0 PA°	2020.0 Sep"	2025.0 PA°	2025.0 Sep"	2030.0 PA°	2030.0 Sep"	2035.0 PA°	2035.0 Sep"	2040.0 PA°	2040.0 Sep"
2	16095-3239	84.00	7.68	83.78	7.65	83.74	7.65	83.69	7.64	83.65	7.64	83.60	7.63	83.55	7.62
4	16195-3054	318.53	23.31	318.36	23.46	318.32	23.49	318.29	23.52	318.25	23.55	318.22	23.58	318.18	23.61

(Continued from page 493)

the uncertainties for early measures are larger (~0.6 arcsec and ~74 degree). These uncertainties are dwarfed by the precisions of the HIPPARCOS and Gaia spacecraft (milli-arcsecond and micro-arcsecond respectively) and their inclusion in the rectilinear analysis presented here would not contribute to the accuracy of that analysis. The rectilinear analysis there is based only on the HIPPARCOS and Gaia positions and the historic measures are shown in Appendix 2 only for completeness, as are the measures from Table 2.

The rectilinear plots for the 10 Sco pairs are presented in Appendix 2.

Table 6 gives the Rectilinear Elements for the 10 pairs, where the column headings, x0, xa, y0, ya, t0, θ0 and ρ0 are defined in Letchford, White and Ernest, 2018a.

Armed with the Rectilinear Elements, it is possible to give an ephemeris for the ρ and PA. This is given in Table 7. Epochs are in the column headings.

8. Determination of the Orbit for Two Sco Pairs.

Following the technique presented in Letchford, White and Ernest, 2018b, it is possible to determine Grade 5 Orbital Elements for pairs that display very short arcs. For this analysis all historic data is considered as is the measure from Table 2.

The orbital elements for two Sco pairs are given in Table 8 and shown graphically in Appendix 3. Column headings in Table 8 are described in Letchford, White and Ernest, 2018b.

Again, armed with these Orbital Elements, it is possible to give an ephemeris for the ρ and PA. These are given in Table 9. Epochs are in the column headings. Units for ρ are arcseconds and units for PA are degrees. These predictions are in exact agreement with the rectilinear predictions of Table 7.

9. Conclusion.

We presented measures for 10 pairs in the constellation of Scorpius using a C14 telescope, lucky imaging, drift scans and the Reduc software. The separations of α Cen AB, as determined from the orbital elements of Pourbaix and Boffin (2016) were used as the image scale and position angle calibrator, where PA calibration was undertaken using drift scans.

Our internal uncertainties are ~0.06 arcseconds in ρ and ~0.06 degree in PA. There is excellent agreement with historic data extrapolated to epoch of observation (~2018.53), and micro-arcsecond positions from the GAIA database where the differences were ~0.05 arcsecond in ρ and ~0.15 degrees in PA.

There is excellent agreement between the extrapolated historic observations and these from Gaia.

In addition, we presented rectilinear elements for 10 Sco pairs and Orbital Elements for two of them. Ephemera are given for these pairs based on both the rectilinear elements are the orbital elements.

10. Acknowledgements.

We acknowledge the use of the following resources:

- SIMBAD Astronomical Database, operated at CDS, Strasbourg, France, https://simbad.u-strasbg.fr/simbad
- The Aladin sky atlas developed at CDS, Strasbourg Observatory, France, https://aladin.u-strasbg.fr
- The Washington Double Star Catalog maintained by the USNO. (WDS), https://ad.usno.navy.mil/wds

- All-sky Compiled Catalogue of 2.5 million stars, 3rd version (ASCC), http://vizier.u-strasbg.fr/viz-bin/VizieR-3?-source=I/280B/ascc
- The Gaia Catalogue (Gaia DR2, Gaia Collaboration, 2018), from VizieR (GAIA DR2), http://vizier.u-strasbg.fr/viz-bin/VizieR-3?-source=I/345/gaia2
- SharpCap astrophotography software developed by Robin Glover, https://www.sharpcap.co.uk

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Measures of Ten Sco Doubles and the Determination of Two Orbits

Appendix 1

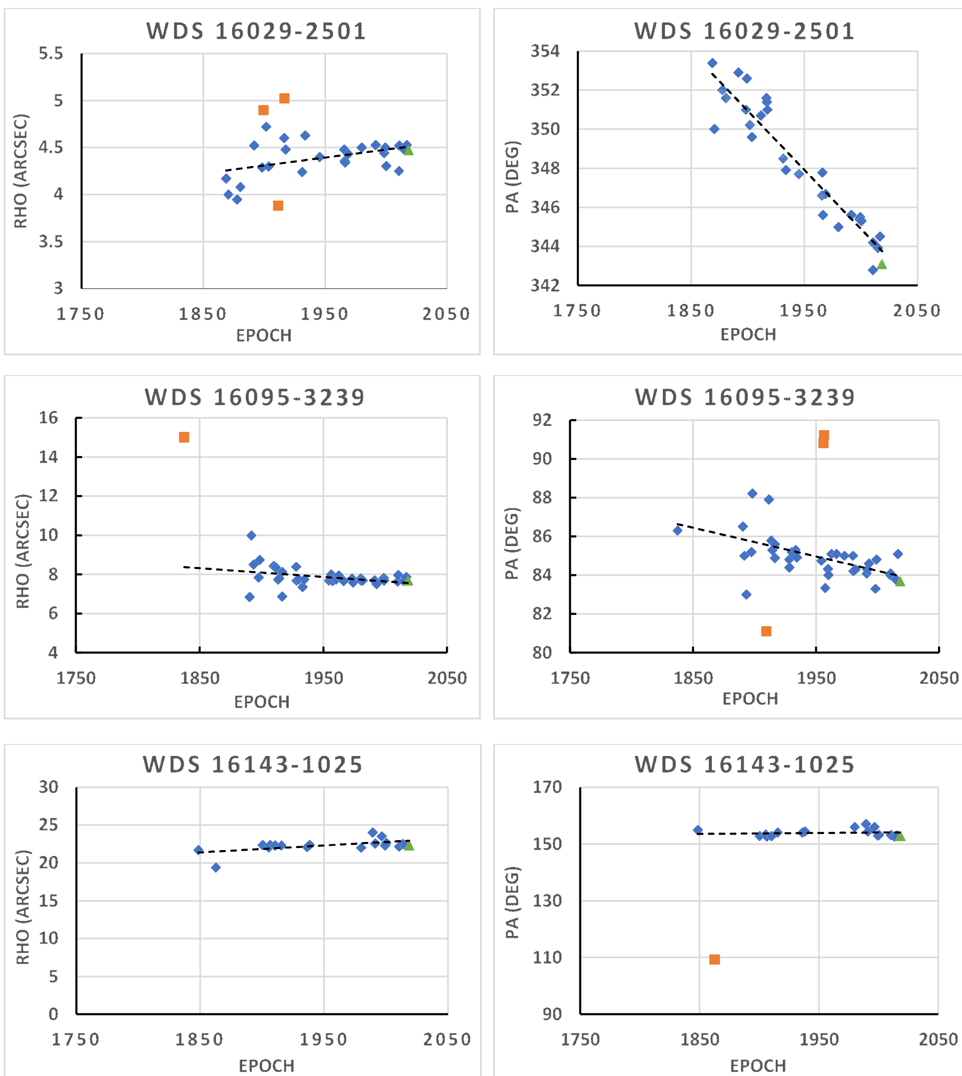
Trends Shown by the Incorporation of Historic Data.

Historic positional measures have been obtained from supplementary catalogues of the WDS. For the 10 pairs a total of 420 observations are available dating from 1783.23.

This Appendix presents the ρ and PA for the 10 Sco pairs. All plots of PA (and ρ) are at the epoch and equinox of observation. Data points in orange have been rejected from the trend. The green points are the measures from this work (from Table 2).

A trend towards better quality data is visible as the spread of data points around the trend line is converging with epoch.

Each plot has been fitted by an unweighted linear trend line and the fitted parameters are given in Table 3 along with the derived correlation coefficient, R^2.



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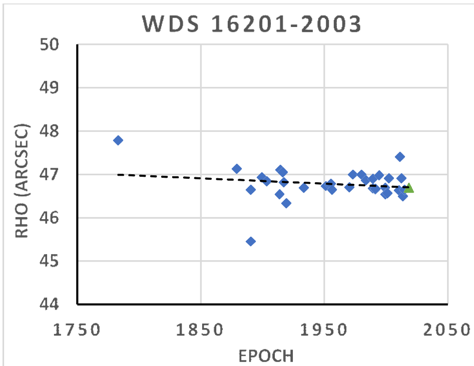
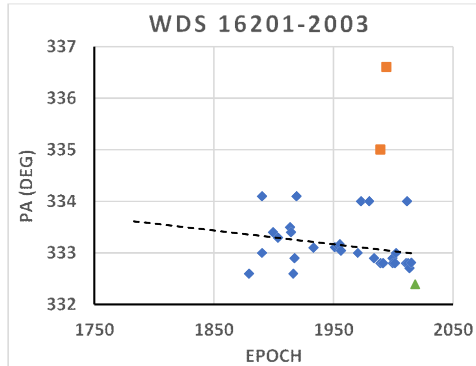
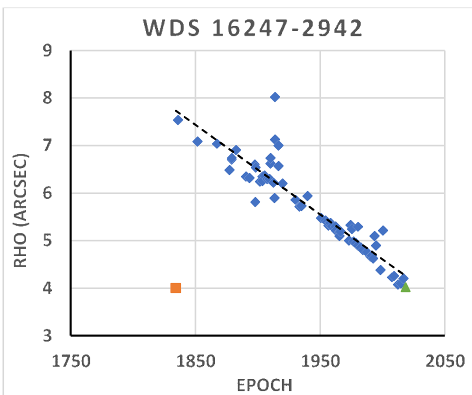
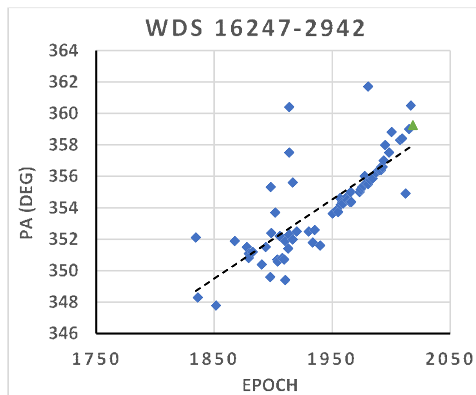
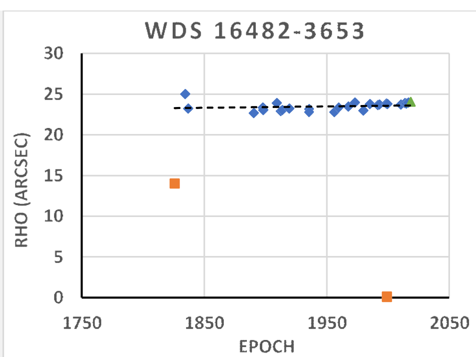
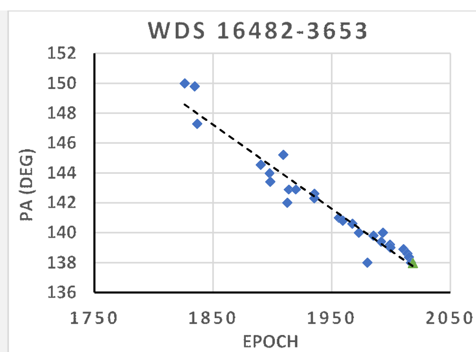


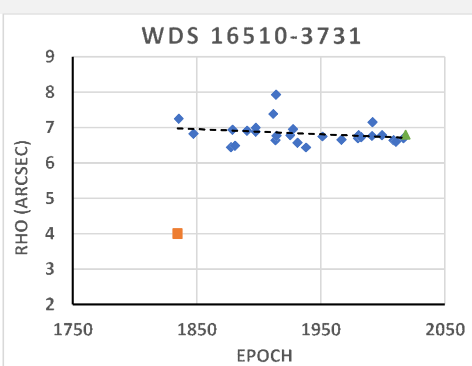


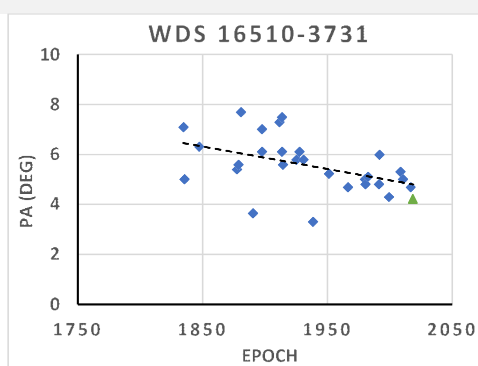




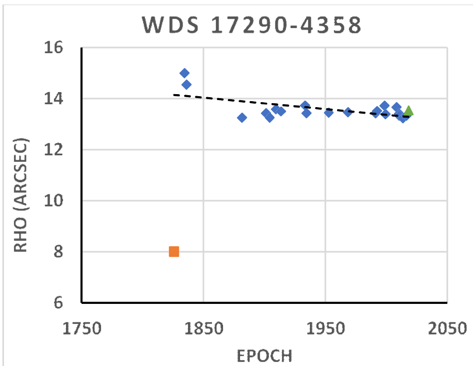


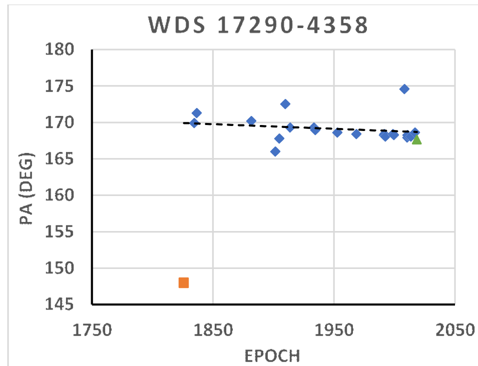


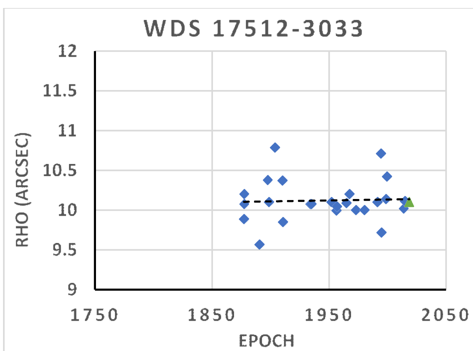


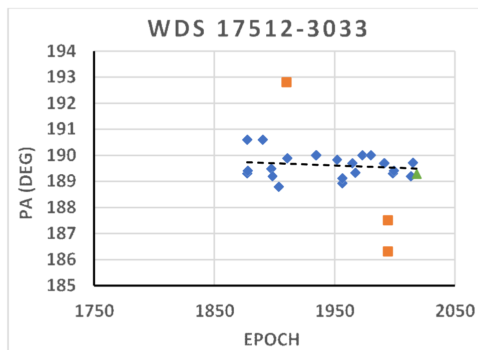


Measures of Ten Sco Doubles and the Determination of Two Orbits









Measures of Ten Sco Doubles and the Determination of Two Orbits

Appendix 2

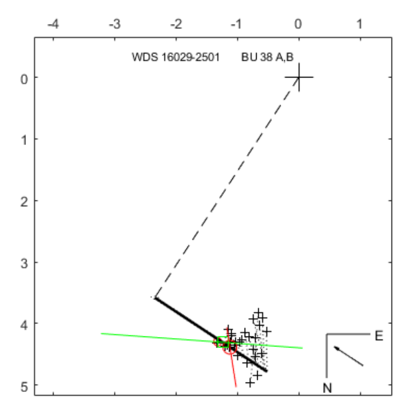
Rectilinear Motion of the Ten Sco Pairs

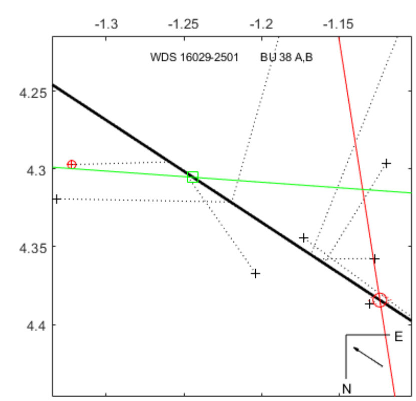
Plots of the rectilinear motion of the 10 Sco doubles are given here. Left hand figures are unzoomed – right hand are zoomed. Historical data from the WDS have been incorporated and their position angles have been precessed from Equinox of date to Equinox J2000.0 using proper motions. The WDS data for 1991.25 (HIP – from the HIPPARCOS mission) are already at Equinox J2000.0. Precessed WDS observations are represented in the plots by a '+'.

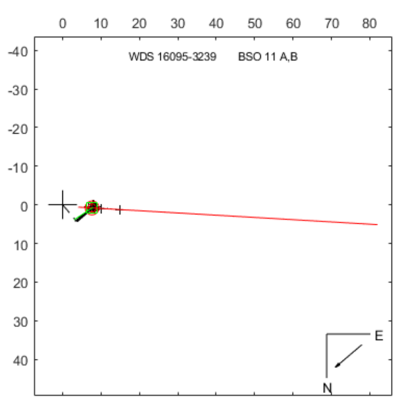
The HIP and GAIA positions are represented by a red circle and green square respectively. The dotted ellipses are the uncertainty ellipses for the t0 (un-zoomed figure for each pair). If they cannot be seen in the plots, it is because of the plot scale. Uncertainty ellipses for the HIP and GAIA were also plotted but in each case they too may be too small to see at the scales that are needed to represent all relevant data.

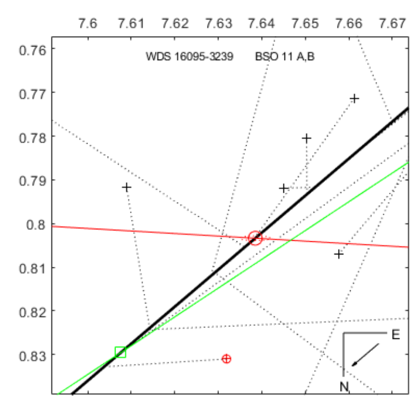
Red line is HIP proper motion and Green is GAIA. The black line is the rectilinear motion based on the HIP and GAIA position. Rectilinear Elements are given in Table 6 and projected r and PA in Table 7.

For additional understanding into the this process, read in Letchford, White and Ernest, 2018b.









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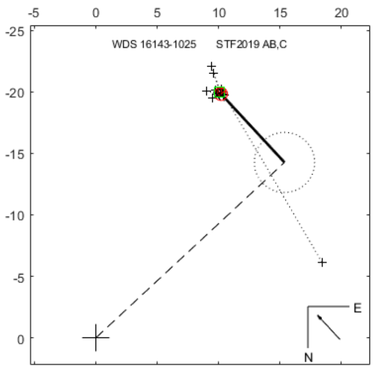
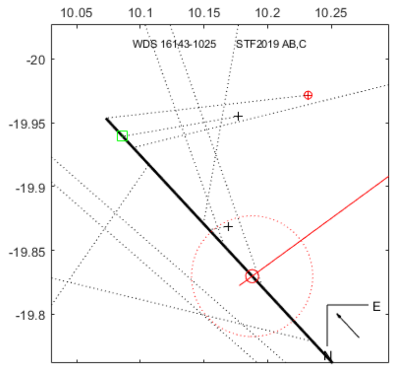
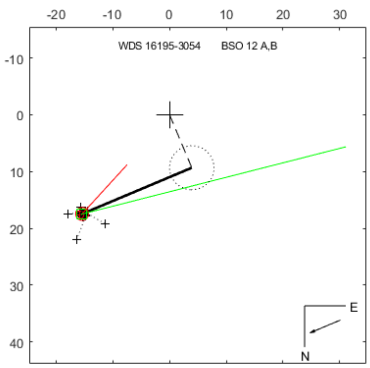
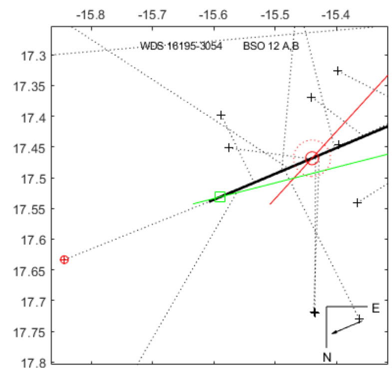
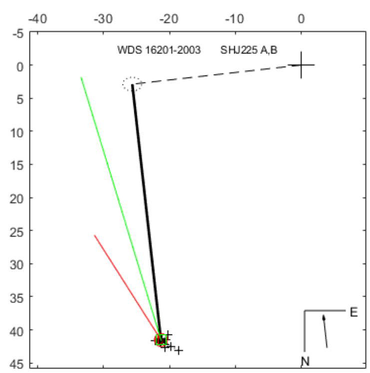
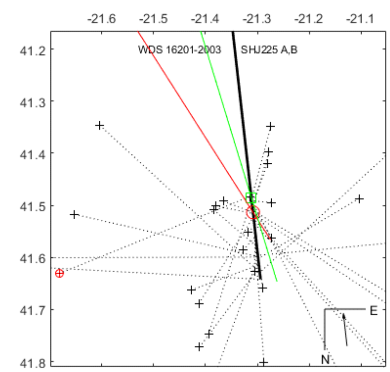


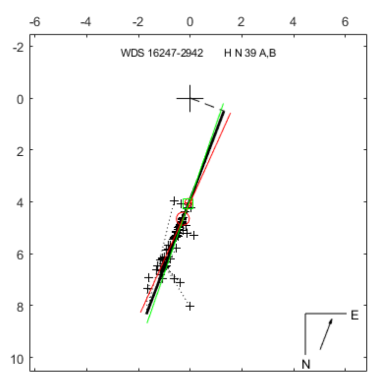


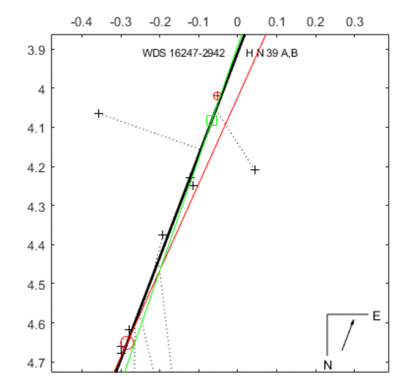




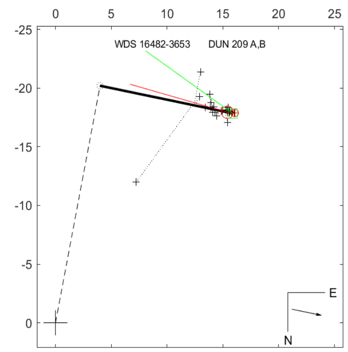


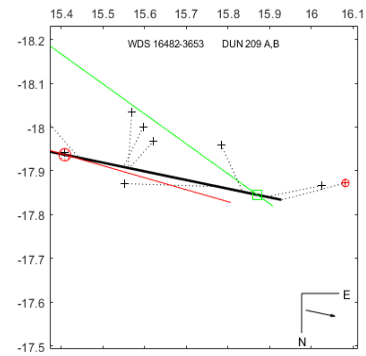


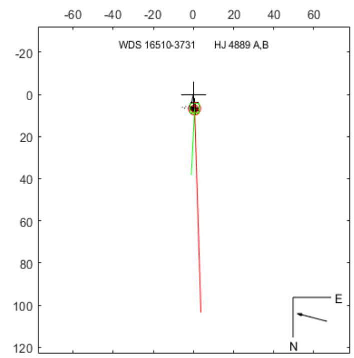


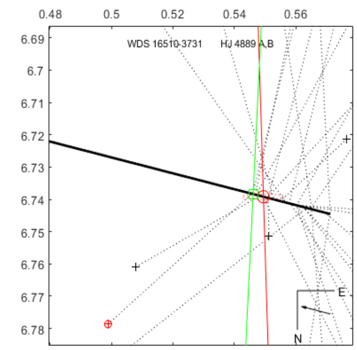


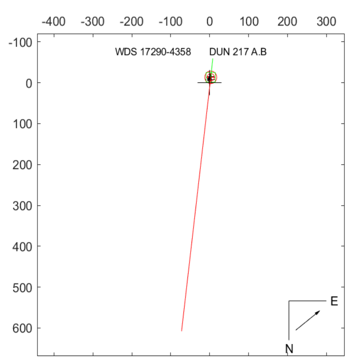
Measures of Ten Sco Doubles and the Determination of Two Orbits

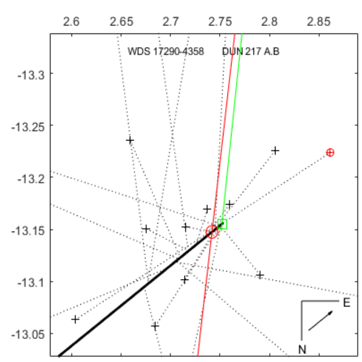


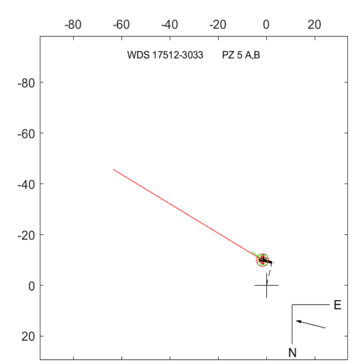


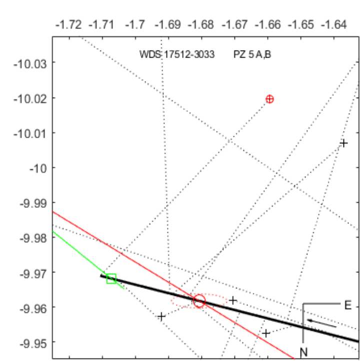












Measures of Ten Sco Doubles and the Determination of Two Orbits

Appendix 3

Orbits Found for the Two Sco Pairs.

The family of orbits for 2 Sco pairs. The best orbit (smallest residuals from historic data) is bolded and the elements are in Table 8. Predicted r and PA based on the Orbital Elements are given in Table 9.