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Speckle observations with PISCO in Merate: VIII. Astrometric measurements of visual binaries in 2007 and new orbits of the multiple system Zeta Aqr

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We present relative astrometric measurements of visual binaries made during the second semester of 2007, with the speckle camera PISCO at the 102 cm Zeiss telescope of Brera Astronomical Observatory, in Merate. Our sample contains orbital couples as well as binaries whose motion is still uncertain. We obtained 283 new measurements of 279 objects, with angular separations in the range $0''.17$ — $4''.4$, and an average accuracy of $0''.014$. The mean error on the position angles is $0^\circ.6$. Most of the position angles were determined without the usual 180° ambiguity with the application of triple-correlation techniques and/or by inspection of the long integration files.
We also present the new orbit we have computed for Zeta Aqr AB (ADS 15971), for which our measurements lead to large residuals with the previously computed orbit. We were also able to compute the elements of the perturbation orbit Bb-P caused by an invisible companion, whose mass is estimated at 0.7 $M_\odot$.

1 Introduction

This paper deals with the results of speckle observations of visual binary stars made in Merate (Italy) during the second semester of 2007 with the Pupil Interferometry Speckle camera and COronagraph (PISCO) on the 102 cm Zeiss telescope of *INAF – Osservatorio Astronomico di Brera* (OAB, Brera Astronomical Observatory). It is the eighth of a series (Scardia et al. 2005, 2006, 2007, 2008b, Prieur et al. 2008, Scardia et al. 2009, Prieur et al., 2009, herein: Papers I to VII), whose purpose is to contribute to the determination of binary orbits. PISCO was developed at *Observatoire Midi-Pyrénées* (France) and first used at *Pic du Midi* from 1993 to 1998. It was moved to Merate in 2003 and used there since.

We briefly describe our observations in Sect. 2. Then we present and discuss the astrometric measurements in Sect. 3. Finally in Sect. 4 we propose new revised orbits for the multiple system Zeta Aqr and derive estimate values for the component masses.

2 Observations and description of the sample

The observations were carried out with the PISCO speckle camera with the ICCD (Intensified Charge Coupled Device) detector belonging to Nice University (France). This instrumentation is presented in Prieur et al. (1998) and our observing procedure is described in detail in Paper VI. For the present observations, thanks to an improvement of our software and a faster computer, we were also able to compute in real time the restricted triple correlation (Aristidi et al., 1997) that we use for resolving the 180 °ambiguity (see Sect. 3.2).

The description of our sample can be found in our previous papers (e.g., Paper VI). It basically includes all the visual binaries for which new measurements are needed to improve their orbits, that are accessible with our instrumentation.

The distribution of the angular separations measured in this paper is displayed in Fig. 1a and shows a maximum for $\rho \approx 0''.7$. The largest separation of $\rho = 4''.4$ was obtained for ADS 11178. The smallest separation was measured for KUI 93, with $\rho = 0''.17$. This is close to the diffraction limit $\rho_d = \lambda/D \approx 0''.13$ with the R filter (i.e. $\lambda = 650$ nm) and the Zeiss telescope whose aperture is $D = 1.02$ m.

The distribution of the apparent magnitudes m_V of the binaries measured in this paper is presented in Fig. 1b and the difference of magnitudes Δm_V between the two components in Fig. 1c. The telescope aperture and detector sensitivity lead to a limiting magnitude of about $m_V = 9$. A careful handling of the image

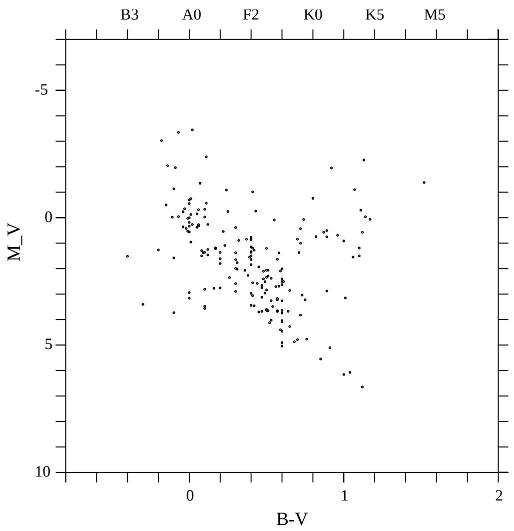

Fig. 2 HR diagram of the binaries measured in Table 1, for which Hipparcos parallaxes were obtained with a relative error smaller than 50% (184 objects).

processing enabled us to measure a few couples with $\Delta m_V > 3$ (Fig. 1c).

Using the Hipparcos parallaxes, we were able to construct the HR diagram of those binaries that is displayed in Fig. 2. We only plotted the objects for which the relative uncertainty on the parallax was smaller than 50%. It can be seen that a large part of the HR diagram is covered by our sample. In the future we would like to acquire a more sensitive detector in order to observe fainter (and cooler) main sequence stars.

3 Astrometric measurements

The astrometric measurements of the observations made during the second semester of 2007 are displayed in Table 1. The format of the first ten columns of this table is the same as for the previous papers of this series. It is described for instance in Paper VI. In Col. 11, we report some information about the secondary peaks of the auto-correlation files: diffuse (Diff.) or elongated (Elon.). The last three columns are dealing with the residuals and will be presented in Sect. 3.3.

The characteristics of the PISCO R and V filters can be found in Table 1 of Paper III. Some objects were observed with no filter because they were too faint. This is indicated with W (for "white" light) in the filter column (Col. 5). The corresponding bandpass is 420 nm corresponding to that of the ICCD detector, with a central wavelength of about 650 nm, close to that of the R filter.

The average values of the errors of the 283 measurements reported in this table are $0''.014 \pm 0''.009$ and $0°.56 \pm 0°.35$ for ρ and θ, respectively. Our error determination procedure is described in detail in Paper III.

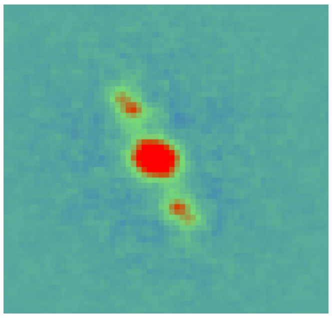

Fig. 3 Auto-correlation of the triple star ADS 11344.

We have noticed some peculiarities in the auto-correlations of ADS 504, 11579, and 16011, with the presence of small symmetric patches (that may be due to detector noise ?). We will re-observe those objects in order to verify that those peculiarities are artefacts.

3.1 The triple system ADS 11344

ADS 11344 is a triple star whose components A, B and C give rise, in the literature, to three different systems: HU 66AB, HU 66BC and STT 351AC (also reported as STT 351AB-C). In fact the C component is the brightest star and B the faintest. As the separation of the AB system is very small, many observers are unable to resolve it and confine themselves to measure AB, as it was a single star (A), with respect to C. This is a source of confusion in the literature [1].In many cases the reported measurements of STT 351AC are in fact those of STT 351AB-C, when the AB system was not resolved. This also happened to us for our first observation of ADS 11344 made in 2004.690 with ($\rho = 0''.802$, $\theta = 25.°7$), reported in Paper II, and wrongly attributed to the STT 351AC system.

The duplicity of the auto-correlation secondary peaks is clear in the observation of ADS 11344 made in 2007.671 (see Fig. 3). We measured them separately and found that the innermost peaks correspond to STT 351AC and the outermost ones to HU 66BC. Finally, each couple composed by the big and small secondary peaks correspond to HU 66AB. This identification is validated with the small residuals that we obtain with Novakovic (2008b)'s orbit of HU 66BC, and with Seymour (2002)'s orbit of HU 66AB (see Table 1).

3.2 Quadrant determination

As our measurements were obtained from the *symmetric* auto-correlation files, the θ values first presented a 180° ambiguity. To try resolving this ambiguity and determine the quadrant containing the companion, we

[1] The last reported observation of STT 351AC in IC4 made in 2005.594 by WSI2006b, with $\rho = 0''.58$ and $\theta = 28.°5$ seems suspicious. It is inconsistent with the trend of the previous observations, especially for ρ.

Table 1 Measurements of binaries with PISCO and residuals with published orbits (begin).

WDS	Name	ADS	Epoch	Fil.	Eyep. (mm)	ρ (")	σ_ρ (")	θ (°)	σ_θ (°)	Notes	Orbit	$\Delta\rho$(O-C) (")	$\Delta\theta$(O-C) (°)
00029+4715	A 800	10	2007.967	W	20	1.584	0.010	113.3*	0.9				
00093+7943	STF 2	102	2007.969	R	20	0.825	0.008	18.0*	0.3		Hei1997	−0.02	1.1
00116+5558	STF 7	143	2007.967	R	20	1.311	0.024	211.4	0.6				
00214+6700	STT 6AB	293	2007.969	R	20	0.653	0.008	154.4*	0.6		Sca2000b	−0.02	−0.1
"	"	"	"	"	"	"	"	"	"		Ole2001	0.04	1.1
00287+3718	A 1504AB	382	2007.972	R	20	0.593	0.008	42.9	1.0				
00366+5609	A 914	504	2007.969	R	20	0.440	0.008	22.6	1.0		Nov2008a	−0.02	−2.8
00373+5801	BU 1097	515	2007.969	R	20	0.510	0.009	72.5*	0.5				
00444+3337	STF 55	618	2007.969	W	20	2.212	0.011	329.7*	0.3				
00480+5127	STF 59AB	659	2007.969	W	20	2.251	0.013	148.0*	0.3				
00550+2338	STF 73AB	755	2007.972	R	20	1.011	0.008	319.8*	0.6		Doc1990b	−0.02	−0.9
01041+2635	COU 351	–	2007.972	W	20	0.797	0.014	243.7	0.4				
01089+4512	AC 13AB	936	2007.964	W	20	0.595	0.009	263.3*	0.9				
01213+1132	BU 4AB	1097	2007.964	R	20	0.594	0.016	107.7*	1.0		Sca2001d	0.06	−1.0
01360+0739	STF 138AB	1254	2007.972	R	20	1.717	0.012	58.2*	0.3				
01501+2217	STF 174	1457	2007.964	R	20	2.841	0.041	164.6*	0.3				
02211+2956	A 962	1792	2007.964	W	20	0.863	0.008	66.6*	0.3				
14455+4223	STT 285AB	9378	2007.542	R	20	0.472	0.016	92.5	0.5		Cou1973b	−0.01	−0.2
14484+2422	STF1884	9389	2007.542	R	20	2.161	0.011	54.9*	0.3				
14497+0759	A 1110AB	9400	2007.543	R	20	0.683	0.008	243.5*	0.8				
14497+4843	STF1890	9406	2007.537	R	20	2.692	0.013	45.1*	0.3				
15018−0008	BU 348AB	9480	2007.545	R	10	0.487	0.003	108.0*	0.3				
15038+4739	STF1909	9494	2007.534	R	20	1.842	0.009	57.9*	0.3		Sod1999	0.01	0.1
15056+1138	STF1907	9498	2007.537	W	20	0.913	0.008	350.6	0.3				
15075+0914	STF1910	9507	2007.567	R	20	4.038	0.031	211.2*	0.3				
15116+1007	A 1116	9530	2007.545	W	20	0.808	0.008	50.9*	0.5				
15183+2650	STF1932AB	9578	2007.534	R	20	1.621	0.010	262.1*	0.5		Hei1965c	−0.01	−0.4
15210+2104	HU 146	9600	2007.534	R	20	0.677	0.039	125.0*	1.7				
15232+3017	STF1937AB	9617	2007.534	R	10	0.510	0.003	139.6*	0.3		WSI2006b	−0.01	−1.3
15245+3723	STF1938Ba,Bb	9626	2007.515	R	20	2.278	0.011	6.5*	0.4		Sod1999	0.03	0.4
15246+5413	HU 149	9628	2007.543	R	20	0.663	0.008	270.5*	0.3				
15261+1810	STF1940	9634	2007.567	R	20	0.415	0.008	331.3	1.0				
15264+4400	STT 296AB	9639	2007.545	R	20	2.091	0.011	275.4*	0.5				
15277+0606	STF1944	9647	2007.545	R	20	0.679	0.013	299.1	0.6				
15278+2906	JEF 1	–	2007.515	R	10	0.288	0.003	144.2*	0.3		Tok1984	0.01	3.1
15300+2530	STF1950	9675	2007.570	R	20	3.297	0.016	90.7*	0.5				
15329+3122	COU 610	–	2007.515	R	10	0.815	0.004	199.1*	0.3				
15348+1032	STF1954AB	9701	2007.551	R	20	4.025	0.020	172.8*	0.3		WSI2004a	0.03	−0.1
15360+3948	STT 298AB	9716	2007.551	R	20	0.979	0.008	175.4*	0.3		Sod1999	−0.02	0.5
15361+4849	HU 652	9718	2007.515	R	20	1.106	0.014	184.3	0.6				
15396+7959	STF1989	9769	2007.551	R	20	0.670	0.008	25.3*	0.3		Hrt2008	0.04	1.3
15405+1840	A 2076	9742	2007.537	R	20	0.716	0.008	184.1	0.7				
15413+5959	STF1969	9756	2007.543	W	20	0.955	0.008	27.4*	0.4		Hei1975b	0.09	−0.7
15427+2618	STF1967	9757	2007.537	R	10	0.697	0.006	112.9*	0.3		Hrt1989	−0.03	0.2
15432+1340	BU 619	9758	2007.570	R	20	0.671	0.009	1.3*	0.9	Diff.			
15487+8337	STF2034	9853	2007.551	R	20	1.106	0.009	109.4*	0.4				
15498+4431	BU 621	9802	2007.583	R	20	0.672	0.010	28.1*	1.0				
15509+1911	A 2078	9809	2007.581	W	20	1.060	0.008	162.6*	0.4				
15568+1229	STF1988	9850	2007.581	R	20	1.885	0.010	250.6*	0.6				
16009+1316	STT 303AB	9880	2007.515	R	20	1.533	0.011	172.1*	0.3				
16030+1359	STF2000	9904	2007.534	R	20	2.564	0.013	227.1*	0.3				
16133+1332	STF2021AB	9969	2007.551	R	20	4.107	0.021	355.6*	0.3		Hop1964b	0.02	0.9
16135+7147	A 1136	9985	2007.570	W	20	0.727	0.011	8.6*	1.0				
16137+4638	A 1642	9975	2007.534	R	20	0.753	0.009	182.1*	0.5		Hrt2001b	0.03	−0.5
16145+0531	STF2023	9974	2007.534	R	20	1.925	0.010	223.8*	0.3				

Table 1 — *continued*

WDS	Name	ADS	Epoch	Fil.	Eyep. (mm)	ρ (")	σ_ρ (")	θ (°)	σ_θ (°)	Notes	Orbit	$\Delta\rho$(O-C) (")	$\Delta\theta$(O-C) (°)
16153+0416	STF2027	9980	2007.534	R	20	1.894	0.019	80.8	0.4				
16160+0721	STF2026	9982	2007.537	W	20	3.385	0.017	17.9*	0.3		Hei1963a	0.00	−0.5
16231+4738	STF2047	10038	2007.545	R	20	1.836	0.019	324.1	0.3				
16238+6142	STF2054AB	10052	2007.543	R	20	0.985	0.008	351.1*	0.3				
16279+2559	STF2049	10070	2007.551	R	20	1.125	0.008	194.6*	0.5				
16289+1825	STF2052AB	10075	2007.543	R	20	2.209	0.011	121.3*	0.3		Sod1999	0.05	−0.0
16309+0159	STF2055AB	10087	2007.543	V	20	1.413	0.008	35.3*	0.3		Hei1993b	−0.04	0.2
16309+3804	STF2059	10093	2007.551	R	20	0.376	0.012	185.9	1.0				
16326+4007	STT 313	10111	2007.551	R	20	0.931	0.008	130.2*	0.3				
16362+5255	STF2078AB	10129	2007.567	R	20	3.151	0.016	104.0*	0.3				
16438+5133	HU 664	10189	2007.567	R	20	0.498	0.009	303.2	1.4				
16448+3544	STF2097AB	10193	2007.570	W	20	1.930	0.017	79.2*	0.6				
16458+3538	STF2101AB	10203	2007.594	R	20	4.104	0.021	47.7*	0.3				
16483+0244	BU 43	10217	2007.581	W	20	1.373	0.014	55.5*	0.4				
16514+0113	STT 315	10230	2007.567	R	20	0.633	0.008	314.0*	0.3		Doc2007d	−0.00	0.1
16540+2906	A 350	10253	2007.581	W	20	0.580	0.014	146.8*	1.0				
16564+6502	STF2118AB	10279	2007.545	R	20	1.054	0.008	66.5	0.3		Sca2002d	−0.10	−0.9
16567+1408	STT 318	10270	2007.551	W	20	2.811	0.014	242.9*	0.3				
16581+1509	STT 319	10277	2007.567	R	20	0.847	0.008	64.3	0.8				
16588+0358	STF3107AB	10285	2007.545	W	20	1.443	0.008	73.1*	0.4				
16594+1419	STT 321	10294	2007.567	W	20	0.584	0.008	14.2*	0.9				
17020+0827	STF2114	10312	2007.690	R	20	1.334	0.014	194.4*	0.3				
17047+1936	PRY 2AB	10326	2007.592	R	20	1.843	0.009	228.2*	0.3				
17053+5428	STF2130AB	10345	2007.567	R	20	2.363	0.012	10.6*	0.3		Hei1981b	0.04	1.8
17082−0105	A 1145	10355	2007.592	R	20	0.658	0.011	349.0*	0.7		WSI2006b	0.02	0.3
17096+0356	HEI 894	–	2007.592	R	20	0.549	0.012	21.7	1.3				
17131+5408	STF2146AB	10410	2007.581	W	20	2.680	0.017	224.4*	0.4				
17166−0027	A 2984	10429	2007.592	R	20	0.839	0.008	11.7*	0.5		Ole1993	−0.19	−0.3
17237+3709	STF2161Aa-B	10526	2007.594	R	20	4.036	0.020	319.5*	0.3				
17237+3709	MCA 48Aa,Ab	10526	2007.594	R	10	0.218	0.013	31.7	3.6	Diff.			
17240−0050	STF2156	10518	2007.594	W	20	3.769	0.019	35.9*	0.3	Elon.			
17246+1536	STF2160	10528	2007.668	R	20	3.780	0.019	65.9*	0.3	Diff.			
17266+3546	STF2168	10558	2007.581	W	20	2.319	0.012	201.2*	0.3				
17290+5052	STF2180	10597	2007.567	R	20	3.041	0.018	259.3*	0.3				
17320+0249	STT 331AB	10614	2007.584	W	20	1.013	0.008	349.8*	0.3				
17350+6153	BU 962AB	10660	2007.655	R	20	1.222	0.008	322.0*	0.3		Sod1999	−0.05	0.0
17400−0038	BU 631	10696	2007.671	R	10	0.260	0.005	89.8	0.5		Hei1996a	−0.01	3.9
17403+6341	STF2218	10728	2007.595	R	20	1.494	0.008	312.4*	0.3				
17412+4139	STF2203	10722	2007.567	R	20	0.743	0.009	294.0	0.8				
17434+3357	HO 560	10742	2007.592	W	20	1.320	0.008	262.9*	0.3				
17464+0542	STF2212	10779	2007.671	W	20	3.226	0.016	340.4*	0.3				
17506+0714	STT 337	10828	2007.592	R	20	0.541	0.009	168.2	1.3		Doc1990a	0.04	2.0
17512+4454	STF2242	10849	2007.655	R	20	3.387	0.017	326.0	0.3				
17520+1520	STT 338AB	10850	2007.655	R	20	0.825	0.008	165.5	0.3				
17533+4000	BU 130	10875	2007.655	R	20	1.579	0.016	110.6*	0.3				
17541+2949	AC 9	10880	2007.655	W	20	1.097	0.008	241.1*	0.4	Elon.			
17564+1820	STF2245AB	10905	2007.655	R	20	2.623	0.013	111.1*	0.3				
18014+6557	STF2284	11016	2007.685	R	20	3.594	0.023	191.5*	0.3	Diff.			
18018+0118	BU 1125AB	10990	2007.668	R	10	0.508	0.003	135.4*	0.6		Pop2000a	−0.08	−2.3
18070+3034	AC 15AB	11077	2007.668	R	20	1.008	0.013	305.2*	0.3		Sod1999	0.03	1.8
18096+0609	STF2283	11110	2007.668	R	20	0.609	0.008	56.2	1.6				
18113+6915	STF2307	11178	2007.685	W	20	4.398	0.071	205.4*	0.3				
18118+3327	HO 82AB-C	11149	2007.668	R	20	0.712	0.011	218.4*	0.7				
18121+2739	STF2292	11155	2007.671	R	20	0.899	0.008	273.9	0.5				

Table 1 — *continued*

WDS	Name	ADS	Epoch	Fil.	Eyep. (mm)	ρ (")	σ_ρ (")	θ (°)	σ_θ (°)	Notes	Orbit	$\Delta\rho$(O-C) (")	$\Delta\theta$(O-C) (°)
18126−0329	A 83	11154	2007.690	W	20	0.752	0.014	303.4	0.8				
18126+3836	BU 1091	11170	2007.668	W	20	0.719	0.008	320.5*	0.6				
18218+2130	BU 641	11287	2007.671	R	20	0.798	0.008	341.0*	0.6				
18239+5848	STF2323AB	11336	2007.685	R	20	3.757	0.056	348.5*	0.3	Diff.	Nov2006e	0.01	−0.3
18253+4846	STT 351AC	11344	2007.671	R	20	0.753	0.011	24.6	0.8				
18253+4846	HU 66BC	11344	2007.671	R	20	0.928	0.008	28.0	0.6		Nov2008b	0.02	0.1
18253+4846	HU 66AB	11344	2007.671	R	20	0.183	0.011	222.5	2.2		Sey2002	−0.02	−0.4
18269+0625	STT 350AB	11349	2007.687	R	20	1.853	0.011	165.7*	0.4				
18278+2442	STF2320	11373	2007.688	R	20	1.119	0.011	359.4*	0.3				
18295+2955	STF2328AB	11397	2007.688	W	20	3.698	0.018	71.4*	0.3				
18310+0123	STF2324AB	11410	2007.688	W	20	2.393	0.035	148.5*	0.3				
18314+0628	STF2329	11420	2007.688	W	20	4.283	0.021	43.2*	0.4				
18320+0647	STT 354	11432	2007.723	R	20	0.592	0.008	209.0	1.2				
18360+1144	STT 357	11484	2007.693	W	10	0.386	0.005	78.3	1.4	Diff.	Val1981d	0.03	1.0
"	"	"	2007.698	W	10	0.389	0.008	78.2	1.5		Val1981d	0.03	0.9
"	"	"	2007.701	W	10	0.375	0.004	78.7	0.6		Val1981d	0.02	1.4
18384+0850	HU 198	11524	2007.690	R	20	0.483	0.013	128.1	0.4		Nov2007d	0.02	−2.4
18384+3603	STF2362	11534	2007.690	R	20	4.317	0.036	186.6*	0.3				
18389+5221	STF2368AB	11558	2007.655	R	20	1.897	0.013	140.5*	0.3				
18413+3018	STF2367AB	11579	2007.769	R	10	0.382	0.004	75.8*	1.1		Pbx2000b	−0.00	0.5
18443+3940	STF2382AB	11635	2007.728	R	20	2.363	0.015	348.7*	0.5		WSI2004b	−0.04	0.5
"	"	"	"	"	"	"	"	"	"		Nov2006e	−0.00	0.4
"	"	"	2007.778	R	20	2.383	0.017	348.6*	0.3		WSI2004b	−0.02	0.4
"	"	"	"	"	"	"	"	"	"		Nov2006e	0.02	0.3
18443+3940	STF2383Cc-D	11635	2007.728	R	20	2.399	0.023	78.9*	0.3		Doc1984b	0.04	−0.3
"	"	"	2007.775	R	20	2.398	0.014	79.0*	0.9		Doc1984b	0.04	−0.2
18455+0530	STF2375AB	11640	2007.655	R	20	2.540	0.013	119.0*	0.3				
18458+3431	STF2390	11669	2007.690	R	20	4.195	0.029	155.2*	0.3				
18469+5920	STF2410	11697	2007.693	R	20	1.678	0.016	86.1	0.7				
18472+3125	STF2397	11685	2007.693	W	20	3.883	0.028	266.9*	0.3	Diff.			
18540+3723	BU 137AB	11811	2007.698	R	20	1.571	0.011	162.4	0.5				
18545+2037	STF2415	11816	2007.690	R	20	1.972	0.020	289.7*	0.5				
18549+3358	STT 525AB	11834	2007.698	R	20	1.791	0.016	129.8*	0.3	Diff.			
18559+0323	A 2193	11844	2007.698	W	20	0.884	0.014	354.3	0.6				
18571+2606	STF2422	11869	2007.668	R	20	0.752	0.008	69.6	0.7				
18576+3209	A 260	11879	2007.698	W	20	0.907	0.009	244.5	0.7				
18581+4711	AG 366	11899	2007.698	R	20	1.494	0.015	190.8	0.4				
18588+0207	MIL 6	11891	2007.701	W	20	0.546	0.017	86.2	0.6				
18594+2936	STF2430	11914	2007.699	W	20	1.544	0.012	186.7*	0.3				
19019+1910	STF2437	11956	2007.668	R	20	0.592	0.014	11.2	1.6		Sca2008c	0.02	0.8
19037+3545	STF2448	12002	2007.701	R	20	2.466	0.017	190.6	0.3				
19042+3245	BRD 4	12008	2007.701	W	20	2.535	0.013	310.6*	0.3				
19055+3352	HU 940	12033	2007.701	R	20	0.533	0.035	196.1	2.3		Hei2001	0.04	3.8
19070+1104	HEI 568	–	2007.723	R	10	0.301	0.004	273.0*	0.3				
19078+3856	STF2469AB	12075	2007.723	R	20	1.262	0.022	127.2*	0.5				
19079+2948	STF2466AB	12071	2007.723	W	20	2.384	0.012	102.6*	0.6				
19126+1651	BU 139AB	12160	2007.655	R	20	0.649	0.014	134.3	0.6				
19159+2727	STT 371AB	12239	2007.688	R	20	0.889	0.011	160.1*	0.4				
19160+1610	STT 368AB	12236	2007.723	R	20	1.146	0.009	218.7	0.8				
19169+6312	STF2509	12296	2007.688	R	20	1.798	0.009	328.7*	0.3				
19177+2302	BU 248AB	12287	2007.723	R	20	1.703	0.018	127.8*	0.4	Diff.			
19185+0105	STF2492AB	12289	2007.731	R	20	3.184	0.038	2.6*	0.3	Diff.			
19186+2157	STF2499	12298	2007.731	W	20	2.579	0.013	323.5*	0.3				
19186+5358	A 1393	12315	2007.731	W	20	0.719	0.009	253.5*	0.3				
19202+3411	HU 1300	12334	2007.731	W	20	0.732	0.008	183.2*	0.8				
19252+0227	STF2513	12414	2007.731	W	20	2.008	0.011	328.4*	0.6				

Table 1 — *continued*

WDS	Name	ADS	Epoch	Fil.	Eyep. (mm)	ρ (")	σ_ρ (")	θ (°)	σ_θ (°)	Notes	Orbit	$\Delta\rho$(O-C) (")	$\Delta\theta$(O-C) (°)
19252+3708	HJ 1395AB	12427	2007.731	W	20	2.832	0.014	63.3	0.3				
19266+2719	STF2525	12447	2007.789	R	20	2.151	0.025	289.6*	0.5		Hei1984b	0.06	−0.6
19269+1204	A 1181	12452	2007.699	R	20	0.672	0.008	199.1*	0.7				
19307+2758	MCA 55Aa,Ac	12540	2007.770	R	10	0.350	0.006	103.3*	0.4	Diff.	Sca2008a	−0.03	−1.5
19334+6203	STF2553	12626	2007.731	W	20	0.986	0.009	127.7*	0.3				
19346+1808	STT 375	12623	2007.701	R	20	0.625	0.015	183.0	1.0				
19389+5150	BU 656	12758	2007.701	R	20	0.916	0.032	270.4	1.2				
19406+6240	STF2574	12803	2007.731	R	20	0.492	0.013	88.4	0.6				
19411+1349	KUI 93	–	2007.728	R	10	0.168	0.011	314.1	1.1		Doc2007d	−0.01	−1.4
19426+1150	STT 380AB	12808	2007.753	R	10	0.403	0.003	76.8*	0.7				
19429+4043	STT 383AB	12831	2007.701	R	20	0.822	0.011	15.7	0.5				
19438+3819	STT 384AB	12851	2007.753	R	20	1.038	0.008	196.4*	0.5				
19450+4508	STF2579AB	12880	2007.688	R	20	2.646	0.013	220.2*	0.3		Sca1983a	−0.01	−0.8
19456+3337	STF2576AB	12889	2007.753	R	20	2.871	0.014	160.3*	0.4		Sod1999	0.00	0.1
19458+4033	STT 385	12904	2007.753	R	20	1.242	0.014	50.4*	0.9				
19471+3321	HU 758	12930	2007.723	W	20	0.896	0.026	144.8	1.4				
19479+2414	DA 10	12948	2007.753	R	20	0.667	0.011	307.0*	0.4				
19482+7016	STF2603	13007	2007.770	R	20	3.141	0.016	19.6*	0.3				
19484+2212	STF2584	12957	2007.723	W	20	1.906	0.010	293.6	0.4				
19486+2458	STF2586AB	12964	2007.753	W	20	3.759	0.028	226.0*	0.3	Diff.			
19487+1149	STF2583AB	12962	2007.669	R	20	1.432	0.008	105.1*	0.3				
19487+3519	STT 387	12972	2007.778	R	10	0.553	0.004	125.6*	0.6		WSI2006b	−0.01	−2.0
19515+2332	BU 978	13030	2007.770	W	20	1.032	0.011	58.3*	0.7				
19524+2551	STT 388AB	13050	2007.778	R	20	3.873	0.019	137.2*	0.3				
19525+2227	HO 580	13055	2007.770	R	20	0.699	0.017	274.8*	2.2				
19535+2405	DJU 4	–	2007.770	R	20	1.336	0.016	245.8*	0.3		Cve2007c	0.02	−0.5
19540+1518	STF2596	13082	2007.669	R	20	2.056	0.020	299.6	0.3				
19556+5226	STF2605AB	13148	2007.775	R	20	2.898	0.041	175.1*	0.4	Diff.			
19576+1524	A 1663AB	13166	2007.778	W	20	1.293	0.008	236.6*	0.3				
19579+4216	STF2607AB-C	13186	2007.778	R	20	2.998	0.015	288.6*	0.3	Diff.			
19584−0214	AC 12	13178	2007.778	R	20	1.458	0.013	298.8*	0.7				
19585+3317	STF2606AB	13196	2007.775	W	20	0.728	0.009	144.8*	0.7				
19586+3806	STF2609	13198	2007.775	R	20	1.954	0.015	22.0*	0.4				
19591+3532	STF2610AB	13204	2007.783	W	20	4.272	0.021	295.5*	0.3				
19594+3206	A 378	13212	2007.778	W	20	0.887	0.008	293.6*	0.5				
20010+3742	BU 1289AB	13262	2007.783	W	20	0.633	0.030	54.8*	0.9				
20017−0012	H 1 93AB	13259	2007.783	W	20	1.827	0.022	297.7*	0.5				
20020+2456	STT 395	13277	2007.729	R	20	0.802	0.008	123.8	0.3				
20027+2939	COU1473	–	2007.728	W	20	0.559	0.008	347.2	0.9				
20028+1435	STF2616	13290	2007.783	W	20	3.548	0.044	266.8*	0.3	Diff.			
20035+3601	STF2624AB	13312	2007.775	R	20	1.945	0.021	174.2*	0.3				
20040+1221	A 1194	13314	2007.789	W	20	1.000	0.025	315.4*	0.3				
20043+3033	STF2626	13329	2007.789	R	20	1.013	0.035	126.5*	1.5				
20051−0418	BU 56	13334	2007.789	R	20	1.355	0.008	186.6*	0.7				
20056+6342	STF2642AB	13392	2007.789	R	20	1.710	0.023	185.6	0.6				
20074+3543	STT 398AB	13405	2007.843	R	20	0.952	0.009	82.7*	0.7				
20080+4223	A 382	13415	2007.843	R	20	1.678	0.008	94.7*	0.3	Diff.			
20137+2414	STF2653	13543	2007.843	R	20	2.878	0.017	274.4*	0.4	Diff.			
20144+4206	STT 403AB	13572	2007.723	R	20	0.951	0.015	170.6*	0.5				
20153+2536	BU 983AB	13589	2007.843	R	10	0.467	0.005	183.8*	0.4	Diff.			
20181+4044	STF2666AB	13672	2007.854	R	20	2.758	0.014	244.9*	0.3				
20184+5524	STF2671AB	13692	2007.854	R	20	3.713	0.019	336.8*	0.3				
20198+4522	STT 406	13723	2007.854	R	20	0.356	0.008	101.1*	0.3		Hei1976	−0.08	−3.9
20303+1054	BU 63AB	13920	2007.688	R	20	0.916	0.008	348.5*	0.4				

Table 1 — *continued*

WDS	Name	ADS	Epoch	Fil.	Eyep. (mm)	ρ (")	σ_ρ (")	θ (°)	σ_θ (°)	Notes	Orbit	$\Delta\rho$(O-C) (")	$\Delta\theta$(O-C) (°)
20318+4933	BU 1136	13976	2007.753	R	20	0.575	0.015	215.2*	0.5				
20335+0527	STF2696AB	13997	2007.778	W	20	0.546	0.014	297.9	1.1				
20356+3510	STF2702	14045	2007.723	W	20	3.204	0.016	205.3*	0.3				
20377+3322	STF2705AB	14078	2007.906	R	20	3.172	0.016	261.6*	0.3				
20396+4035	STT 410AB	14126	2007.775	R	20	0.843	0.013	6.1	0.5				
20423+5723	BU 152	14196	2007.843	R	20	1.159	0.022	82.3*	1.3				
20450+1244	BU 64AB	14238	2007.844	R	20	0.651	0.008	351.7	0.3		Bdl2007a	−0.01	−1.1
20511+5125	BU 155AB	14370	2007.770	R	20	0.677	0.026	36.3	1.4				
20541+4507	STT 422	14411	2007.854	W	20	2.587	0.014	332.0*	0.3				
20548+3242	STT 418	14421	2007.789	R	20	0.977	0.019	285.0	0.7				
20585+5028	STF2741AB	14504	2007.789	R	20	1.966	0.010	25.5*	0.3				
20593+1534	STT 424AB	14505	2007.844	R	20	0.511	0.008	305.9	0.4				
20598+2004	STF2739	14515	2007.914	W	20	3.331	0.017	252.3*	0.3	Elon.			
21008+4635	BU 156	14561	2007.778	W	20	1.025	0.012	235.0*	0.4				
21018+3916	STF2746	14558	2007.778	R	20	1.201	0.020	320.6*	0.7				
21031+0132	STF2744AB	14573	2007.844	R	20	1.273	0.015	114.3*	0.4		Pop1969b	0.06	5.6
21093+3131	COU1333	–	2007.770	W	20	0.628	0.017	255.2	1.2				
21112+5620	DOO 16	14739	2007.789	W	20	1.102	0.008	28.5*	0.8				
21143+4109	STT 432	14778	2007.914	R	20	1.333	0.010	114.7*	0.3				
21197+0931	STF2786	14856	2007.950	R	20	2.738	0.014	188.4*	0.3				
21208+3227	STT 437AB	14889	2007.950	R	20	2.402	0.012	20.6*	0.6				
21252+3129	A 1220	14957	2007.950	W	20	1.624	0.019	157.5*	0.7				
21280+4305	HO 160	15000	2007.950	W	20	2.036	0.010	182.5*	0.5				
21330+2043	STF2804AB	15076	2007.958	R	20	3.291	0.050	356.8*	0.8				
21521+2748	HO 171	15401	2007.914	W	20	0.750	0.014	341.9	0.9	Elon.			
21555+5232	STT 456AB	15460	2007.958	R	20	1.615	0.012	36.3*	0.3				
22009+4338	HO 175AB	15547	2007.844	R	20	0.868	0.028	318.9*	0.7				
22029+4439	BU 694AB	15578	2007.844	R	20	1.000	0.008	6.1*	0.3				
22044+1339	STF2854	15596	2007.966	R	20	1.691	0.008	82.7*	0.5				
22071+0034	STF2862	15639	2007.966	R	20	2.498	0.012	95.4*	0.3				
22110+2429	EGG 4	–	2007.844	W	20	0.563	0.008	149.6*	0.3				
22110+6324	STF2879AB	15712	2007.958	R	20	0.776	0.013	232.3	1.0				
22117+5743	A 625AB	15726	2007.969	R	20	0.547	0.018	80.1	1.2				
22126+3013	HO 179AB	15738	2007.879	W	20	0.899	0.008	280.0*	0.7				
22128+1355	HU 978	15735	2007.879	W	20	1.129	0.011	206.1*	0.3				
22136+5234	BU 991	15756	2007.964	W	20	0.657	0.008	137.8*	0.5				
22145+0759	STF2878AB	15767	2007.966	R	20	1.495	0.008	115.1*	0.3				
22146+2934	STF2881	15769	2007.915	R	20	1.311	0.011	75.8*	0.3				
22158+4354	HO 180AB	15794	2007.915	W	20	0.758	0.008	239.5*	1.0				
22202+2931	BU 1216	15843	2007.969	W	20	0.887	0.011	278.0*	0.3				
22206+5349	BU 379	15856	2007.950	W	20	1.107	0.014	335.1*	0.5				
22269+6343	KR 59	15954	2007.950	W	20	1.752	0.009	344.9*	0.4				
22288−0001	STF2909AB	15971	2007.966	R	20	2.042	0.010	170.8*	0.3		Ole2004a	−0.13	−5.2
"	"	"	"	"	"	"	"	"	"		This paper	−0.03	−1.9
22302+2228	HU 388	15992	2007.966	R	20	0.494	0.008	57.1*	0.9		Doc2008c	−0.02	−1.6
22305+6137	HU 981	16011	2007.964	W	10	0.298	0.003	215.3*	0.9				
22345+4046	COU1838Aa,Ab	–	2007.969	W	20	1.097	0.019	164.8*	0.9	Diff.			
22426+4401	A 414AB	16204	2007.882	W	20	1.706	0.009	194.1*	0.3				
22431+4710	STT 476A-BC	16214	2007.967	R	20	0.488	0.008	301.1*	0.7				
22470+4446	A 189AB	16266	2007.967	W	20	0.991	0.008	26.0*	0.6				
22496+6633	STF2948	16298	2007.972	R	20	2.685	0.022	4.4*	0.5				
22507+5107	HLD 54	16307	2007.972	R	20	1.874	0.012	17.1*	0.8				
22514+2623	HO 482AB	16314	2007.972	R	20	0.489	0.016	18.5*	1.3		Sta1982b	−0.00	2.1
22520+5743	A 632	16326	2007.972	R	20	0.511	0.008	137.9*	0.7		Hei1991	0.02	−3.2
22564+2257	COU 240	–	2007.844	R	20	0.766	0.013	291.1	1.2				

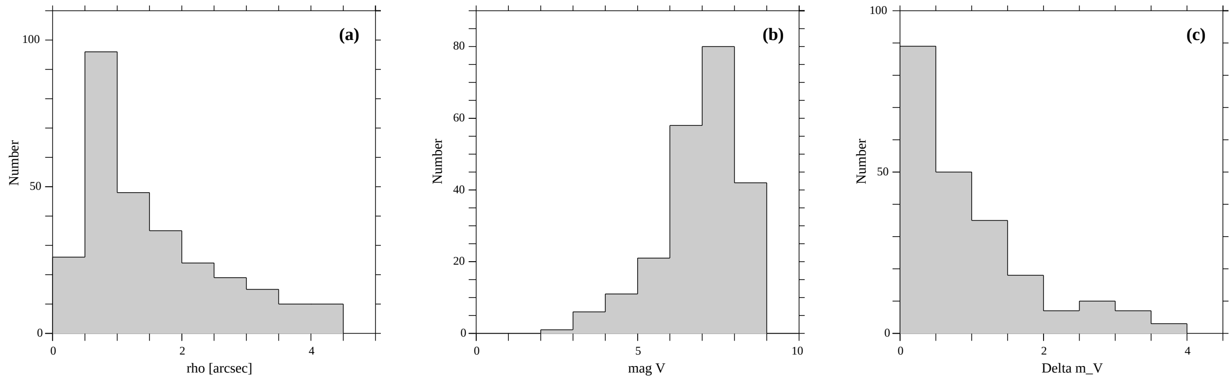

Fig. 1 Distribution of the angular separations of the 283 measurements of Table 1 (a), of the visual magnitudes of the corresponding objects (b) and of the differences of magnitude between the two components of those binaries (c).

have used Aristidi et al. (1997)'s method by computing and analysing restricted triple correlation files. For the couples with the largest separations, a straightforward determination could be done when the companions were visible in the long integration files.

As a result, in Table 1, we are able to give the non-ambiguous (or "absolute") position angles of 213 out of 283 measurements, i.e. 76% of the total. They are marked with an asterisk in Col 9. Otherwise, our angular measurements were reduced to the quadrant reported in the "Washington Double Star Catalogue" (Mason et al, 2009, hereafter WDS Catalogue).

Our "absolute" θ values are consistent with the values tabulated in the WDS Catalogue for all objects except for ADS 10, 10905, 11558, 15954, 16204, 16307, 16958 and 17122. In all those cases, however, a clear and high contrast between the two secondary peaks of the triple correlation is observed, which is a good indication of the validity of our quadrant determination. In the following, we discuss each case using the usual convention of numbering the quadrants (Q) from 1 to 4 to indicate the North-East, South-East, South-West and North-West quadrants, respectively.

ADS 10: Our value of Q=2 is consistent both with the space-based Tycho measurement of 1991.75 (Høg et al. 2000) and with Douglass et al. (1997)'s measurement of 1992.878. It is likely that the quadrant Q=4 reported in the WDS Catalogue comes from the other 12 observations listed in the "Fourth Catalogue of Interferometric Measurements of Binary Stars" (Hartkopf et al. 2009, hereafter IC4). The two components of ADS 10 have a similar brightness, with $\Delta m_V = 0.16$, which well accounts for the difficulty of determining the quadrant. Furthermore, most of those observations of IC4 were made in V, whereas we observed with no filter, which corresponds to a bandpass close to that of the R filter (see Sect. 2). There can exist a quadrant inversion between V and R, since the spectral type of the primary component is A0 and is probably associated to a cooler companion.

ADS 10905: Our quadrant determination Q=2 in R is consistent with the values we found in 2004.690 in Merate (Paper II) and in 1998.654 at the Pic du Midi with a 2m-telescope (Scardia et al., 2000a). It is however in disagreement with the quadrant Q=4 reported for the other 58 observations listed in IC4, made in V. Like ADS 10, this discrepancy can be due to a quadrant inversion that is likely since $\Delta m_V = 0.12$, with a spectral class of A0 III for the primary.

ADS 11558: Our value of Q=2 in R is inconsistent with the fourth quadrant given for the 27 measures listed in IC4, all made in V. The Wilson spectral classes are A1n, for the primary and G0 for the secondary (WDS Catalogue notes). The small difference in magnitude, $\Delta m_V = 0.14$, might account for the quadrant inversion since the G0 component could appear as the brightest one in R. We already observed this object in 2004.657 (Paper II) but the seeing conditions were not good enough for enabling the quadrant determination.

ADS 15954: Our quadrant Q=4 obtained with no filter is in agreement with Tycho measurement of 1991.69 (Høg et al. 2000), and in disagreement with the other 9 observations reported in IC4, made in V. For this object, the components have a larger brightness difference, with $\Delta m_V = 0.4$, and the spectral type of the primary is O9V.

ADS 16204: Here also, our value of Q=3 obtained with no filter is in agreement with Tycho measurement of 1991.76 (Høg et al. 2000) and in disagreement with the other 7 observations reported in IC4, all made in V. The very small value of $\Delta m_V = 0.06$ well explains the difficulty of determining the good quadrant. Furthermore, we noticed an inversion in the magnitudes of the components tabulated in the WDS Catalogue (the faintest magnitude being placed in the column of the primary component and vice-versa), which might be another source of error. We observed this binary also on 2006.951 (Paper VI) but the low signal-to-noise ratio did not allow us to determine the quadrant.

Table 1 — *continued*

WDS	Name	ADS	Epoch	Fil.	Eyep. (mm)	ρ (")	σ_ρ (")	θ (°)	σ_θ (°)	Notes	Orbit	$\Delta\rho$(O-C) (")	$\Delta\theta$(O-C) (°)
22565+6252	STF2961	16394	2007.950	W	20	1.870	0.009	347.5*	0.3				
23103+3229	BU 385AB	16561	2007.879	R	20	0.657	0.008	85.8*	0.8		Lin2008a	−0.01	−0.2
23162+5424	A 1482	16641	2007.967	W	20	1.315	0.011	87.7*	0.4				
23188+2513	STF3000	16664	2007.972	W	20	3.397	0.017	50.2*	0.3				
23420+2018	STT 503AB	16937	2007.879	W	20	1.060	0.008	132.3*	0.3				
23439+0715	STF3033	16958	2007.972	W	20	3.006	0.024	3.2*	0.6				
23487+6453	STT 507AB	17020	2007.964	R	20	0.705	0.012	317.1*	0.4		Zul1977b	−0.02	2.2
23522+4331	BU 728	17063	2007.879	W	20	1.246	0.008	8.3	0.3				
23576+4804	A 799	17122	2007.915	W	20	2.019	0.010	190.9*	0.3				
23579+5723	STF3047AB	17126	2007.964	W	20	1.122	0.017	70.5*	0.8				
23590+5315	HLD 59AB	17141	2007.964	W	20	1.173	0.008	12.6*	0.4				
23590+5545	STF3049AB	17140	2007.964	R	20	3.073	0.017	325.9*	0.3				
23595+3343	STF3050AB	17149	2007.915	R	20	2.196	0.011	334.3*	0.5		Sta1977b	0.11	−0.1

Notes: In column 9, the exponent * indicates that the position angle θ could be determined without the 180° ambiguity. Orbit references in column 12: Bdl2007a = Brendley & Hartkopf (2007), Cou1973b = Couteau (1973), Cve2007c = Cvetkovic (2007), Doc1984b = Docobo & Costa (1984), Doc1990a = Docobo & Costa (1990a), Doc1990b = Docobo & Costa (1990b), Doc2007d = Docobo & Ling (2007), Doc2008c = Docobo & Ling (2008), Hei1963a = Heintz (1963), Hei1965c = Heintz (1965), Hei1975b = Heintz (1975), Hei1976 = Heintz (1976), Hei1981b = Heintz (1981), Hei1984b = Heintz (1984), Hei1991 = Heintz (1991), Hei1993b = Heintz & Strom (1993), Hei1996a = Heintz (1996), Hei1997 = Heintz (1997), Hei2001 = Heintz (2001), Hop1964b = Hopmann (1964), Hrt1989 = Hartkopf et al. (1989), Hrt2001b = Hartkopf & Mason (2001), Hrt2008 = Hartkopf et al. (2008), Lin2008a = Ling (2008), Nov2006e = Novakovic & Todorovic (2006), Nov2007d = Novakovic (2007), Nov2008a = Novakovic (2008a), Nov2008b = Novakovic (2008b), Ole1993 = Olevic et al. (1993), Ole2001 = Olevic & Jovanovic (2001), Ole2004a = Olevic & Cvetkovic (2004), Pop1969b = Popovic (1969), Pop2000a = Popovic et al. (2000), Pbx2000b = Pourbaix (2000), Sca1983a = Scardia (1983), Sca2000b = Scardia et al. (2000b), Sca2001d = Scardia (2001), Sca2002d = Scardia et al. (2002), Sca2008a = Scardia et al. (2008a), Sca2008c = Scardia et al. (2008c), Sey2002 = Seymour (2002), Sod1999 = Söderhjelm (1999), Sta1977b = Starikova (1977), Sta1982b = Starikova (1982), Tok1984 = Tokovinin (1984), Val1981d = Valbousquet (1981), WSI2004a = Mason et al. (2004a), WSI2004b = Mason et al. (2004b), WSI2006b = Mason et al. (2006), Zul1977b = Zulevic (1977).

ADS 16307: Our quadrant Q=1 determined in R is in agreement with Tycho determination of 1991.72 (Høg et al. 2000), but in disagreement with the other 5 observations reported in IC4, and made in V. This discrepancy is difficult to explain since $\Delta m_V = 0.81$. The primary spectral class is A0.

ADS 16958: Here conversely, our quadrant Q=1 determined without filter is consistent with all the observations reported in IC4 (all made in V) but not with the Tycho measurement (Q=3) of 1992.07 (Høg et al. 2000) whose quadrant was adopted by the WDS Catalogue. The spectral class is F2 and the difference in magnitude of the components is significant: $\Delta m_V = 0.33$.

ADS 17122: Our determination of Q=3 made with no filter is in agreement with Tycho measurements of 1991.67 (Høg et al. 2000), but not with the first quadrant (adopted by the WDS Catalogue) of the other 7 observations reported in IC4, all made in V. The difference in magnitude of the components is $\Delta m_V = 0.17$ and the spectral class A5.

3.3 Comparison with published ephemerides

The $(O - C)$ (Observed minus Computed) residuals of the measurements for the 65 systems with a known orbit in Table 1 are displayed in Cols. 13 and 14 for the separation ρ and position angle θ, respectively. The orbital elements used for computing the ephemerides were retrieved from the "Sixth Catalogue of Orbits of Visual Binary Stars" (Hartkopf & Mason, 2009, hereafter OC6). The corresponding authors are given in Col. 12, using the style of the OC6 references.

The residuals reported in this table were computed with the most recent orbits found in OC6, but for some objects (i.e., for ADS 293 and 11635), we also give the $O - C$ values relative to old orbits found in the previous issues of OC6, when they are still valid. For STF 2909 AB, we also give the residuals obtained with our new orbits presented in Sect. 4, for comparison.

For most of the orbits used for computing the residuals reported in Table 1, the equinox of the node Ω was 2000.0, and the correction to be applied to the computed position angle was negligible. Such a correction

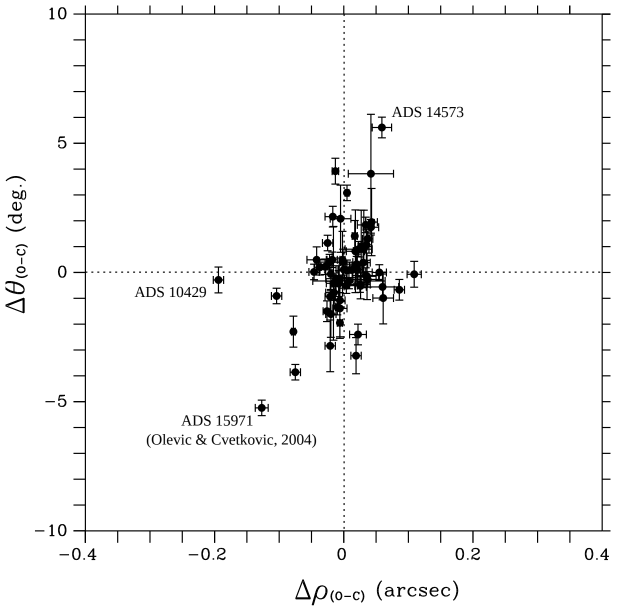

Fig. 4 Residuals of the measurements of Table 1 from the published orbits.

was only necessary for ADS 9378 (equinox: 1950.0) and for ADS 9969, 16314 and 17149 (equinox: 1900.0).

Fig. 4 shows that the residuals are well centered around the origin, with a rather large scatter that can be explained by the (old) age of many orbits. The mean values computed with the residuals of Table 1 are $<\Delta\rho_{O-C}>= 0''.00 \pm 0''.05$ and $<\Delta\theta_{O-C}>= 0°.2 \pm 1°.7$. The small values obtained for those offsets provide an additional validation of our calibration made with a grating mask (see Paper III), which is in good agreement with the measurements made by the other observers. In the following, we examine the cases of ADS 10429, 14573 and 15971 that appear with the largest residuals in Fig. 4.

ADS 10429: this couple is difficult to measure because of a large brightness difference between the two components: $\Delta m_V = 2.5$. This may explain why there are only 3 speckle measurements in IC4: two made in 1995 by the US Naval Obs. in Washington, and one obtained by our group in 2004.659 with $\rho = 0''.867 \pm 0''.006$ and $\theta = 10°.3 \pm 0°.9$ (Paper II). All the other measurements were obtained visually. The revision of Olevic et al (1993)'s orbit would be too premature, because it is still satisfactory in terms of position angle, and also because the orbital arc covered by the companion is very small.

ADS 14573: here also the orbital arc covered by the companion is too small to justify a new computation: the resulting orbit would be completely undetermined (grade 5).

ADS 15971: the recent orbit of STF 2909 AB computed by Olevic & Cvetkovic (2004) leads to rather large residuals with both our measurement and the last ones reported in IC4. The companion is moving closer to the primary than expected by Olevic's orbit. We propose a new orbit in the next section.

4 Revised orbits of the multiple system Zeta Aqr - ADS 15971

4.1 Visual orbit AB of Zeta Aqr

ADS 15971 – STF 2909 AB – HIP 110960 – Zeta Aqr, is a famous binary star, with more than 1200 measurements made since its discovery in 1777, by Christian Mayer in Mannheim with a Bird mural quadrant. It was first reported in Mayer's catalogue (actually the first catalogue of binary stars) that contained 89 couples and was published in the "Astronomische Jahrbuch für 1784". The first real measures of ADS 15971 were made by W. Herschel in 1779 with a 6-inch telescope.

This object was observed with PISCO at the Pic du Midi in 1998 and in Merate in 2004, 2005 and 2007, and two of us have also contributed to this effort with micrometer observations. MS used a 23-cm refractor in Merate in 1982 and 1984, and the 38-cm GPO in La Silla in 1992. RWA obtained an annual series of measures between 1990 and 2008 using the 20-cm refractor at Cambridge University Observatories. The whole list of measurements used for computing the new orbits was kindly provided by B. Mason from the WDS data base maintained by the United States Naval Observatory. We also added a recent measurements made with a micrometer by RWA with the 20-cm Cambridge Observatory refractor (Argyle, 2009).

We first computed the preliminary orbital elements with the analytical method of Kowalsky (1873). We then used them as initial values for the least-squares method of Hellerich (1925), which leads to an improvement of the orbital elements with an estimation of their errors.

The total list of 1211 measurements was obtained with a wide range of telescopes (with apertures from 7-cm to 4-m). To obtain a more robust solution, we rejected the aberrant measurements for which the residuals were larger than 1.7-σ, i.e., with $\Delta\rho_{O-C} > 0''.31$ and $\Delta\theta_{O-C} > 4°6$. This resulted in a selection of 1189 observations. The final orbital elements are presented in Table 2 with the errors obtained by Hellerich's method. For all the tables of this section, we use the same format as for the previous papers. A full description can be found, for instance in Paper VI. The mean standard deviations of the residuals are $0''.22$ and $2°.9$ for ρ and θ, respectively. This scatter is explained by the large range of instruments and epochs, and also by the perturbation of a third invisible body (see below).

The apparent orbit is shown in Fig. 5 as a solid line and the observational data plotted as small crosses or, in the case of PISCO observations, as small circles.

4.2 Perturbation orbit Bb-P of Zeta Aqr

The zoomed part of the orbit in Fig. 5b on the most recent observations exhibits an oscillatory trend which betrays the presence of a third star perturbing the orbital motion of the AB couple. This property was first noticed by Strand (1942), who published the first orbits for the close and wide pairs simultaneously. A series of subsequent studies (Strand 1942, Franz 1958, Harrington 1968, Heintz 1984c) precised the parameters of the perturbation orbit with a period of 25.5 years and a semi-major axis of $0''.06$. The mass of the third star was estimated at 0.22 $M_\odot$ by Harrington (1968) or at 0.4 $M_\odot$ by Heintz (1984c).

It is difficult to locate this companion, since the masses of the A and B components are similar and the presence of a companion "a" close to A or another companion "b" close to B would produce similar effects on the AB orbit. On the basis of parallax observations, Franz (1958) linked it to a possible Bb pair, whereas Heintz (1984) favoured a hypothetical Aa pair.

At optical wavelengths, Weigelt (1983) found a close companion to Zeta Aqr A with a separation of $0''.064 \pm 0.005$ in 1978.964, which is much too small to correspond to the perturbation orbit. In near infrared, a companion was detected close to Zeta Aqr B at $0''.17$ by McCarthy et al (1982) with the Kitt Peak 3.8-m telescope. The angular separation and the estimated mass were both in good agreement with Harrington's orbit. We will assume in this paper that this observation is valid and that the perturbation is due to the Bb couple detected by McCarthy et al. According to the convention used by the OC6, the perturbation orbit will be called Bb-P, since its corresponds to the orbit of B relative to the center of mass of the outer Bb system.

Using all the photographic and speckle measurements published since 1923, we computed the residuals of our orbit of ADS 15971 AB in Cartesian coordinates, from which we derived the elements of the perturbation orbit Bb-P and its uncertainties with Hellerich (1925)'s least-squares method. To our knowledge, the uncertainties on those elements had never been computed before. The results are presented in Tables 2, 3 and in Fig. 6.

The $(O - C)$ residuals obtained with the combination of orbits AB and Bb-P, restricted for reasons of space to the observations made after 2002, are given in Table 4. The corresponding mean standard deviations are $0''.11$ and $1^\circ.25$ for ρ and θ, respectively, which is about half of the values obtained with the orbit AB alone (see Sect. 4.1). The combined ephemerides for 2009–2020 are presented in Table 5.

Our two orbits are still temporary since only half of the AB orbit has been monitored yet. The orbital elements of the main orbit are still poorly known (for instance the period has an uncertainty of 10%).

Table 3 New ephemeris of the perturbation orbit Bb-P of ADS 15971. Here ρ' is the angular separation between B and the center of mass of the Bb system. The angular separation of Bb is estimated at 3.0 ρ' (see text).

Epoch	ρ' ($''$)	θ ($^\circ$)	Epoch	ρ' ($''$)	θ ($^\circ$)
2009.0	0.058	81.7	2015.0	0.067	159.0
2010.0	0.059	96.2	2016.0	0.067	169.8
2011.0	0.060	110.1	2017.0	0.069	180.2
2012.0	0.062	123.4	2018.0	0.069	190.5
2013.0	0.064	135.9	2019.0	0.068	200.9
2014.0	0.065	147.8	2020.0	0.067	211.6

4.3 Discussion: nature of the perturbing component

In the SIMBAD data base, the two components A and B of Zeta Aqr are identified separately as HD 213052 (F3V, $m_V = 4.42$) and HD 213051 (F6IV, $m_V = 4.5$). Some physical parameters derived for this system from our orbital elements are presented in Table 6. Both the linear size of a (Col. 5) and $\mathfrak{M}_{\rm total}$ (Col. 6) were computed from our orbital elements and using the Hipparcos parallax revised by van Leeuwen (2007) and reported in Col. 3. Using the relation we established for IV-type stars (Scardia et al, 2008c, p 380) we derived a total mass of 3.59 ± 0.96 $M_\odot$. The theoretical value for two stars F3V+F6IV is $\mathfrak{M}_{\rm total} = 2.64$ $M_\odot$ (Straizys & Kuriliene, 1981). The mass of the invisible companion could thus be as large as 0.95 ± 0.96 $M_\odot$. Unfortunately the corresponding uncertainty prevents us from drawing any conclusion about the nature of the invisible companion.

The mass of the b component can also be estimated with the measurement of angular separation of Bb made by McCarthy et al (1982), which was $\rho = 0.''17$ in 1981.94. The ephemerides for this epoch with our orbit Bb-P lead to $\rho' = 0''.056$. Since $\rho/\rho' = (M_B + M_b)/M_b$, it comes: $M_B/M_b = 2.0$ and $M_b = 0.65$ $M_\odot$. Hence the b component could be a late-type main sequence star of type K3–K5. McCarthy et al (1982) measured its flux in near infrared and found $K = 6.0$ mag with a strong infrared excess $K - L = 1.3 \pm 0.2$ mag, redder than that expected of even the coolest main-sequence stars and corresponding to a colour temperature of 1440 K. It is thus expected to be much fainter than the A, B components, ($\Delta m_V > 4$ mag.) which well explains the absence of detection with visual observations.

5 Conclusion

In the second semester of 2007, we obtained 283 new measurements of 279 visual binaries with PISCO in Merate, with an average accuracy of $0''.014$ for the angular separation and $0^\circ.6$ for the position angles. The total number of measurements made in Merate since

Table 2 New elements of the visual orbit AB and perturbation orbit Bb-P of ADS 15971.

Orbit	Ω_{2000} (°)	ω (°)	i (°)	e	T (yr)	P (yr)	n (°/yr)	a (″)	A (″)	B (″)	F (″)	G (″)
AB	133.2	273.0	141.7	0.343	1982.733	486.70	0.7397	3.380	−2.05206	−1.68435	−2.20940	2.55557
	±3.4	±9.4	±1.0	±0.029	±4.2	±40	±0.061	±0.023				
Bb-P	20.900	330.3	22.3	0.125	2003.404	25.822	13.942	0.062	0.06045	−0.00734	0.01092	0.05751
	±26	±29	±10	±0.018	±0.652	±0.139	±0.0751	±0.012				

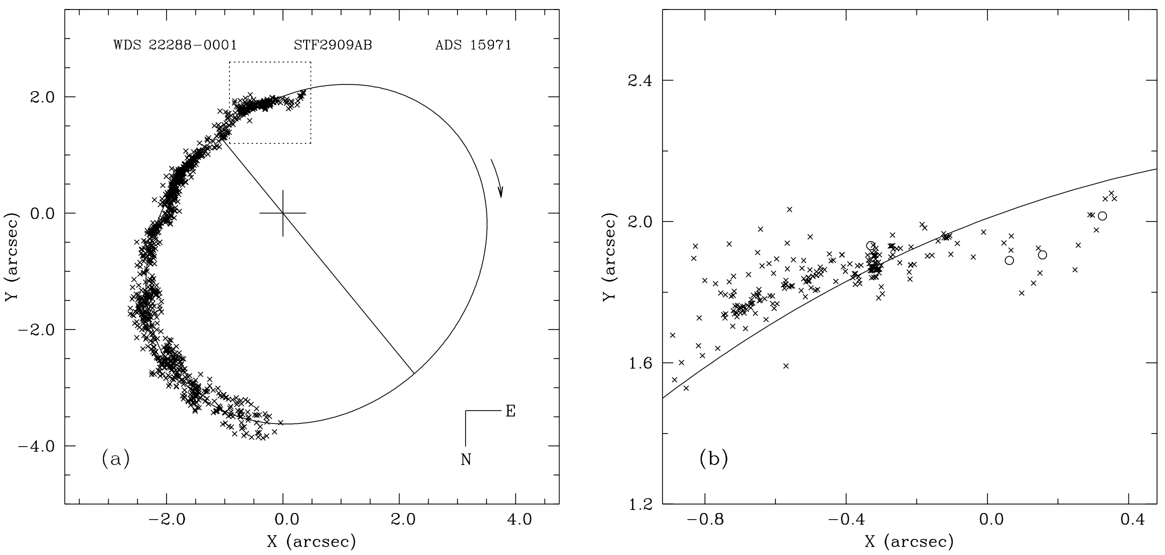

Fig. 5 New orbit of ADS 15971 AB (a) with enlarged part in (b), corresponding to the dotted square in (a). Plotted as a solid line, it is actually the orbit of the center of mass of the Bb couple relative to the component A marked as a big cross. The four observations of PISCO, including the one made at Pic du Midi by Scardia et al. (2000a) on 1998.879 (the first from left), are printed as circles.

2004 now approaches 1600. This work is thus a good contribution to the continuing monitoring of long period visual binary systems, which is important for refining systemic stellar masses.

We obtained new orbital elements of the perturbation orbit Bb-P of Zeta Aqr and were able, for the first time, to compute their errors. Infrared observations with a 4-m class telescope would be very useful to constrain this orbit, or more basically to provide a clear confirmation of the presence of the invisible companion at the right position.

Acknowledgements. We thank the members of the United States Naval Observatory, Washington DC, for kindly sending on request some lists of measurements of visual binaries. This work has made use of the "Fourth Catalogue of Interferometric Measurements of Binary Stars" (http://ad.usno.navy.mil/wds/int4), the "Sixth Catalogue of Orbits of Visual Binary Stars" (http://ad.usno.navy.mil/wds/orb6), the Washington Double Star Catalogue maintained at the U.S. Naval Observatory (http://ad.usno.navy.mil/wds/wds) and the SIMBAD data base (http://simbad.u-strasbg.fr/simbad) operated by the *Centre de Données Astronomiques de Strasbourg* (France).

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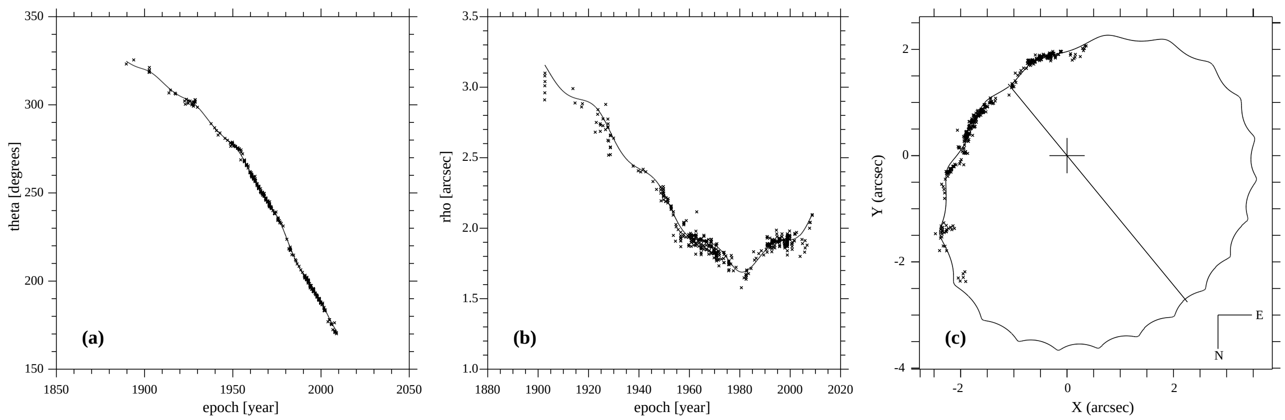

Fig. 6 New orbit of ADS 15971: combination of the AB and Bb-P orbits (solid line) compared to all the photographic and speckle measurements (crosses): (a) position angle vs epoch, (b) angular separation vs epoch, and (c) orbit in the plane of the sky.

Table 4 ADS 15971: O-C residuals obtained with the combination of the orbits AB and Bb-P. The symbol ^{P} indicates PISCO measurements. Measurements with "Ary" in Col. 4 were made by RWA with a 20 cm refractor.

Epoch	$\Delta\rho$ (O-C) ($''$)	$\Delta\theta$ (O-C) ($^\circ$)	Observer
2002.531	0.039	0.511	WSI
2002.800	0.006	−0.031	Ary
2003.740	−0.049	0.621	Alz
2003.804	0.020	−0.147	Ary
2003.937	−0.152	−3.273	Dal
2004.669	−0.048	−0.680	WSI
2004.750	−0.030	0.082	Alz
2004.800	−0.012	−0.418	Ary
2004.878	-0.083^P	-0.161^P	Paper II
2005.732	−0.167	−0.700	WSI
2005.777	−0.069	−0.815	Ary
2005.899	-0.090^P	-0.985^P	Paper IV
2005.937	−0.143	−0.814	Dal
2006.700	−0.148	−2.431	WSI
2006.790	−0.081	−2.273	Alz
2006.810	0.008	−3.038	Ary
2007.639	–	3.050	Cli
2007.700	−0.064	−2.052	WSI
2007.783	−0.027	−1.220	Smr
2007.835	0.041	−2.537	Ary
2007.966	-0.031^P	-1.932^P	This paper
2008.701	0.019	−2.028	Ary
2008.734	−0.006	−1.481	Ant
2008.734	−0.011	−0.781	Ant

Table 5 New ephemeris of ADS 15971 – STF 2909 AB obtained with the combination of the AB and Bb-P orbits.

Epoch	ρ ($''$)	θ ($^\circ$)	Epoch	ρ ($''$)	θ ($^\circ$)
2009.0	2.113	171.2	2015.0	2.313	164.7
2010.0	2.151	169.9	2016.0	2.337	163.9
2011.0	2.188	168.7	2017.0	2.358	163.0
2012.0	2.223	167.6	2018.0	2.375	162.1
2013.0	2.256	166.6	2019.0	2.389	161.2
2014.0	2.286	165.6	2020.0	2.401	160.3

Table 6 Physical parameters of Zeta Aqr AB (a and $\mathfrak{M}_{\rm total}$) derived from the new orbital elements.

m_V	Spec. type	π_{HIP} (mas)	a ($''$)	a (AU)	$\mathfrak{M}_{\rm total}$ $M_\odot$
3.65	F3V+F6IV	35.68	3.38	94.7	3.6
		±1.24	±0.02	±3.4	±1.0

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