ORBITS OF FIVE VISUAL BINARY STARS

B. Novaković

1 Astronomical Observatory, Volgina 7, 11160 Belgrade 74, Serbia

Abstract. We presented here the orbital parameters for five visual binary stars calculated by using the new method which we named Sector Grid Search. Orbital parameters were obtained for the following stars: WDS 00152+2722 = ADS 195, WDS 02202+2949 = ADS 1780, WDS 11550−5606 = HIP 58106, WDS 16256−2327 = ADS 10049 and WDS 16256−2327 = ADS 10045. In addition, their masses, dynamical parallaxes and ephemerides were calculated as well.

Key words: Stars: Binaries: Visual, Methods: Numerical

1. INTRODUCTION

The study of binary stars is a very old branch of astronomy which still plays an important role in a present astronomy. It has a number of aims. Binary stars have been studied for decades to measure accurate the stellar masses, to test the evolutionary models and the star formation theories.

Although the Washington Double Star Catalog (WDS) (Mason et al. 2006) contains a large number of double and multiple systems (over 84000), according to the Sixth Catalog of Orbits of Visual Binary Stars (Hartkopf & Mason 2006) only for about 1900 systems the orbital parameters have been calculated. It is because available data for many systems are not sufficient for an accurate determination of the orbital parameters. It is caused by two main reasons. The number of observers is too small compared with the number of systems and/or the orbital period in some systems is too long compared with a time span since the beginning of systematic measurements. As a result researchers have been pushing to estimate system parameters from ever shorter arcs. The literature on the determination of system parameters of visual binary is a very numerous. Despite such a large number of methods, no one method proposed so far is adequate in the case of a short arc. We presented here a fully automated method for determination of systems parameters from a short arc, which we named Sector Grid Search (SGS). Furthermore, we also presented the systems parameters of five visual binary stars calculated by using SGS method. The orbits of the stars WDS 00152+2722, WDS 02202+2949 and WDS 16256−2327 (pair AB) were previously announced by IAU Commission 26 (2007, Inf. Circ. 162).

The dynamical parallaxes and the individual masses were calculated for stars which belong to the Main Sequence according to the method proposed by Angelov (1993). Trigonometric parallaxes published in the Hipparcos and Tycho Catalogues (ESA 1997) were used in order to calculate the total masses of the systems. The values of the stellar masses as a function of the spectral type, used as reference, have been taken from Schmidt-Kaler (1982). Visual magnitudes and spectral types, presented in Table 3, were taken from WDS catalogue.
2. METHOD

Among the methods presented so far one can find several efficient methods. We will mention here only a few of them which are widely used.

The best known method for determination of system parameters is that of Thiele-Innes-van den Bos (Thiele 1883; van den Bos 1926, 1932; Dommanget 1981). Yet it cannot be expected to handle all possible cases. It requires the knowledge of three normal places and an area constant. Docobo (1985) proposed an analytical method which does not require the knowledge of the area constant. The method is based on a mapping from the interval \((0, 2\pi)\) into the family of Keplerian orbits whose apparent orbits pass through three base points. These points are taken either coinciding with the most reliable measurements or belong to the areas with a maximum of observational evidence in their favor, but do not necessary coincide with actual measurements. The orbits which fits the best to all known measurements is chosen from all generated possible ones. In addition, it has an option allowing the use the radial velocities, being thus useful for the inclinations close to 90° and in the case of a short arc as well.

The numerical methods, based on minimization procedure, which take advantage from computer’s power were proposed by Eichhorn and Xu (1990) and Pourbaix (1994). The method proposed by Hartkopf et al. (1989) also takes advantage from computer power but with a different approach. The orbital parameters are calculated according to the "three-dimensional adaptive grid search" and it requires preliminary knowledge of the period \(P\), epoch of periastron passage \(T\) and eccentricity \(e\).

The most recently Olević & Cvetković (2004) proposed a method suitable for application in the case of short arc which is based on using supplementary, fictive, measurements. In our previous papers (e.g. Novaković 2007) we used this method in order to calculate the orbital parameters and we obtained acceptable results when deal with a short arc. Although we obtained good results with this method, they depend on the choice of the fictive measurements.

We presented here a simple and fully automated method which can give a reliable orbit solution even in the case of a short arc and does not need any subjective initial parameters such as fictive measurements. It consists of several main steps.

The first step in our procedure is to assign the appropriate weights to all measurements according to the weighting rules described in Hartkopf et al. (1989,2001) and rejecting all measurements with errors which do not satisfied 3\(\sigma\) condition. The next step is to divide observed arc in five equal intervals and determining minimum and maximum value of angle separation for every interval \((\rho_{\text{min}}, \rho_{\text{max}})_{i=1,5}\) as well as an average value of position angle for every interval \(\theta_{i=1,5}\) \(^{1}\). Given the set of the five position angles \(\theta_{i=1,5}\) and the five intervals of the angle separations \((\rho_{\text{min}}, \rho_{\text{max}})_{i=1,5}\) we can proceed further. As we know a general equation of the conic section is of the form

\[ \frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \]

\(^{1}\)In order to include the possible measurements errors it is necessary to correct the values of \(\rho_{\text{min}}\) and \(\rho_{\text{max}}\) (correction makes interval a little bit wider). This correction should takes into account a maximum allowed error of 3\(\sigma\).
so the curve has been determined if we have determined the five coefficients $a_{20}, a_{02}, a_{11}, a_{10}, a_{01}$. If the positions of the five points were given the coefficients can be determined by solving system of the five linear equations. We apply an iterative procedure beginning with a $\rho_{\text{min}}$ and increasing the angle separation $\rho$ for step size as many times as we need to reach $\rho_{\text{max}}$. For every combination of the five position angles and the five angle separations the five coefficients are determined by using LU decomposition described in Press et al. (1992). From these five coefficients we can calculate the five orbital parameters $(a, e, i, \Omega, \omega)$ and two dynamical parameters $(P, T)$ can be calculated from the Keplerian equation

\[
\frac{2\pi}{P}(t_j - T) = M(\theta_j, a, e, i, \Omega, \omega).
\]

The last step is minimization of function $D$ defined as

\[
D = \left[ \sum_j w_j ( (x_o - x_c)_j^2 + (y_o - y_c)_j^2 ) \right] / \sum_j w_j.
\]

In this formula, $w_j$ denotes the weight of the $j^{th}$ measurement, $x_o,y_o$ denotes the observed positions and $x_c,y_c$ denotes the calculated positions of the companion. The minimization is done by applying Powell’s method (Press et al. 1992), but with just three degrees of freedom $(P, T, a)$ in order to decrease probability to reach a local minimum which number growing as $\exp(N)$ ($N$-the number of degrees of freedom). For each step in the grid search a set of orbital parameters is calculated and a solution with minimum residuals is accepted as a final solution.

2.1. Test

In order to test efficiency of SGS method we determined the orbital parameters of two visual binary stars which have had orbital parameters already calculated and very reliable. For this test we selected the star WDS 02022+3643 (HD 12376) from the Catalog of Orbits and Ephemerides of Visual Double Stars (Docobo et al. 2001) and the star 16413+3136 (HD 150680) from the Sixth Catalog of Orbits of Visual Binary Stars. In the case of the star WDS 02022+3643 test was made using speckle measurements only, but in the case of the star WDS 16413+3136 test results were obtained using mixed data (visual,speckle,photographic,CCD).

The star WDS 02022+3643 (pair AB) has a very good orbit calculated by Hartkopf et al. (2000). As we wanted to show that method presented here is efficient in the case of a short arc we did not use all measurements available for this star but only a set of 7 measurements from 1994.7086 to 1999.8856 which covered an arc of $\approx 59^\circ$. Similarly, we calculated orbital parameters for binary star WDS 16413+3136 using only a part of available measurements. For the purpose of this study we chose 38 measurements from 1989.3931 to 1999.61 which covered an arc of $\approx 67^\circ$.

Test results are presented in a Table 1. and they show that by using SGS method good results can be obtained even in the case of a short arc.
Table 1: Test results

| Element       | SGS method | Hartkopf et al. 2000 | SGS method | Soderhjelm 1999 |
|---------------|------------|----------------------|------------|-----------------|
| $P_{[yr]}$    | 12.90      | 12.94                | 36.76      | 34.45           |
| $T$           | 1988.82    | 1989.06              | 1966.1     | 1967.7          |
| $a_{['']}$    | 0.155      | 0.150                | 1.40       | 1.33            |
| $e$           | 0.508      | 0.404                | 0.40       | 0.46            |
| $i_{[o]}$     | 68.9       | 67.0                 | 127.4      | 131.0           |
| $\Omega_{[o]}$ | 195.2     | 191.4                | 53.7       | 50.0            |
| $\omega_{[o]}$ | 289.0     | 295.1                | 107.4      | 111.0           |

3. RESULTS AND COMMENTS

In this section we presented results and comments on individual objects.

Table 2. presents the corresponding numerical values for the orbital parameters (epoch J2000) and their estimated formal errors as well as the identifications of the stars in several widely-used catalogs.

Table 3. gives the astrophysical quantities for both components: visual magnitudes, spectral types, absolute visual magnitudes, masses and, in the last two columns, the calculated dynamical parallax and the Hipparcos trigonometric parallax.

Table 4. gives predicted ephemerides for these systems for the period 2008-2012.

The orbits are illustrated in Figures 1-5. The solid curves represent the newly determined orbital parameters, while the dashed curves represent previously published orbital parameters. The solid lines indicate the line of nodes. All measurements are connected with their predicted positions on the new orbit by "O-C" lines. The interferometric measurements are represented of each plot by full circles "•" and all others measurements (visual, photographic) are represented by plus "+". The direction of motion is indicated on the north-east orientation in the lower right of each plot and "+" indicate position of primary star.

**WDS 00152+2722 = J 868.** It was discovered in 1907.78 by Barton (1926) and 15 measurements have been performed till a year 2002. Recently, an additional measurement was carried out by our double star group (Cvetković et al. 2007). Our orbital solution is the first one for this binary star and it was calculated by using set of all 16 measurements. As data about this star are very poor we do not know very much about it. Under the assumption that its components belong to the Main Sequence we estimated the total mass of system $M_{tot} \approx 1.0 \, M_{\odot}$.

**WDS 02202+2949 = A 961.** This binary star was discovered in 1905.87 by Aitken (1906) at Lick Observatory. Previous orbit of this binary have been calculated by Heintz (1969). In order to demonstrate improvement of previous orbit obtained by Heintz we calculated root mean square (rms) of residual values. The obtained rms values are $\Delta \theta = 2.9^\circ$, $\Delta \rho = 0^\circ.039$ (this work), and $\Delta \theta = 2.9^\circ$, $\Delta \rho = 0^\circ.042$ (Heintz’s orbit) what indicates that our orbit solution does improve separation but gives statistically same result for position angle. Our orbital parameters and the Hipparcos parallax yield a total mass of system $M_{tot}$.

\[^2\text{When deriving these values corresponding weights have been taken into account}\]
\approx 3.0 \, M_\odot$. This value is slightly larger than the expected value for this spectral type (on condition that both components belong to the Main Sequence).

**WDS 11550−5606 = HLD 114.** This is a wide binary star discovered in 1882 by Holden (1884). Till the present time 47 measurements have been performed and they cover an arc of \approx 60°. Our orbital parameters are the first ones calculated for this binary and they should be classified as preliminary. The new measurements are necessary to obtain more reliable orbit solution and to understand significant differences between dynamical parallax (this work) and Hipparcos trigonometric parallax. In general, this disagreement could be due to the incorrect orbital solution and/or because at least one of the components does not belong to the Main Sequence. The spectral type of primary star (G3IV/V) suggested that it could lie outside of the Main Sequence.

**WDS 16256−2327 = H 2 19 AB.** It was discovered as early as in 1780.34 by W. Herschel. Though the time interval after the discovery has already exceeded 200 years, available measurements cover a short arc of \approx 28°. This pair is included in the Catalog of Rectilinear Elements (Hartkopf et al. 2006) indicated that it is not a physical. Despite this indication, we calculated system parameters because we think that is not clear yet whether this pair is physical or optical. The rms values are \Delta \theta = 1.9°, \Delta \rho = 0°.147 (this work), and \Delta \theta = 1.8°, \Delta \rho = 0°.148 (linear fit) what is statistically indistinguishable results. Our orbital parameters and Hipparcos parallax yield a total mass of the system $M_{tot} \approx 23.6 \, M_\odot$. As one can expect near 10.0$M_\odot$ (Schmidt-Kaler 1982) for stars of B2V spectral type and slightly over 10.0$M_\odot$ for B2IV spectral type, the obtained value of total mass of the system is reasonable.

**WDS 16256−2327 = BU 1115 DE.** This binary star belong to the same multiple system as the previous one, but it was discovered by Burnham (1894) in 1889.39 at Lick Observatory. The orbital parameters presented here are the first for this binary. The dynamical parallax is $\pi = 0°.00769$, in very good agreement with the Hipparcos parallax $\pi_{HIP} = 0°.00733$, but the total mass of the system ($M_{tot} \approx 5.8 \, M_\odot$ with Hipparcos parallax), calculated with our orbital parameters and either Hipparcos or dynamical parallax, is significantly smaller than expected for B5V spectral type. As we know, combination of the uncertainty of the semi-major axis, of the orbital period and that of the parallax is easily propagated in the standard deviation of the total mass as,

$$
\sigma_M = M_{tot} \sqrt{9(\frac{\sigma_a}{a})^2 + 9(\frac{\sigma_\pi}{\pi})^2 + 4(\frac{\sigma_P}{P})^2}
$$

According to equation (4) the error of total mass is $\sigma_M = 4.0 \, M_\odot$. Taking into account this error, we obtained 9.8 $M_\odot$ as the upper limit for the total mass of this system.
Figure 1: J 868.

Figure 2: A 961.

Figure 3: HLD 114.

Figure 4: H 2 19 AB.
Table 2. Orbital parameters (J2000).

| Name   | ADS | HD | P[yr] | T     | a["] | e   | i["] | Ω[°] | ω[°] |
|--------|-----|----|-------|-------|-------|-----|-------|------|------|
| J 868  | 195 | -  | 1089. | 1725. | 8.48  | 0.367| 75.2  | 68.9 | 352.8|
| 00152+2722 | - | -  | ±153. | ±147. | ±1.06 | ±0.370| ±2.5  | ±3.1 | ±19.4|
| A 961  | 1780| 14394| 143.1 | 14394 | 143.1 | 143.1| 143.1 | 143.1| 143.1|
| 02202+2949 | 12885 | 10892 | ±5.6  | ±5.7  | ±0.057| ±0.095| ±3.9  | ±5.8 | ±8.5 |
| HLD 114 | - | 103493 | 930.  | 2039. | 8.02  | 0.707| 97.7  | 167.4| 59.7 |
| 11550–5606 | - | 58106 | ±98.  | ±91.  | ±0.90 | ±0.109| ±1.5  | ±1.3 | ±7.4 |
| H 2 19 AB | 10049 | 147933 | 2398. | 2327. | 4.25  | 0.675| 135.3 | 77.5 | 226.1|
| 16256–2327 | 7613 | 80473 | ±326. | ±343. | ±0.79 | ±0.322| ±6.9  | ±13.5| ±15.3|
| BU 1115 DE | 10045 | 147888 | 675.5 | 2008.6 | 1.01  | 0.707| 134.8 | 152.7| 260.4|
| 16256–2327 | 7609 | 80461 | ±32.5 | ±34.2 | ±0.15 | ±0.112| ±2.7  | ±4.6 | ±1.1 |

Table 3. Dynamical elements.

| WDS   | m_A–m_B | Sp.  | M_A | M_B | M_A | M_B | π dyn | πHIP ± σπHIP |
|-------|---------|------|-----|-----|-----|-----|-------|--------------|
| 00152+2722 | 12.42 | 12.62 | 12.11 | 12.21 | 0.54 | 0.50 | 79.06 | - |
| 02202+2949 | 9.31  | 8.94  | F5  | 3.46 | 3.09 | 1.33 | 1.41 | 7.69 | 7.48 ± 2.59 |
| 11550–5606 | 7.36  | 7.81  | G3IV/V | 6.18 | 6.63 | 0.88 | 0.82 | 70.50 | 32.33 ± 1.44 |
| 16256–2327(AB) | 5.07 | 5.74 | B2IV B2V | - | - | - | - | 8.27 ± 1.18 |
| 16256–2327(DE) | 7.04 | 8.65 | B5V | 1.47 | 3.08 | 3.06 | 1.97 | 7.69 | 7.33 ± 1.37 |

Table 4. Ephemerides.

| WDS     | Desig. | θ  | ρ  | θ  | ρ  | θ  | ρ  | θ  | ρ  |
|---------|--------|----|----|----|----|----|----|----|----|
|         |        | ["] | ["] | ["] | ["] | ["] | ["] | ["] | ["] |
| 00152+2722...... | 228.3 | 5.817 | 228.5 | 5.855 | 228.6 | 5.892 | 228.8 | 5.929 | 229.0 | 5.967 |
| 02202+2949...... | 277.4 | 0.301 | 275.7 | 0.294 | 274.0 | 0.287 | 272.1 | 0.280 | 274.2 | 0.273 |
| 11550–5606...... | 169.7 | 3.291 | 169.4 | 3.264 | 169.2 | 3.235 | 169.0 | 3.205 | 168.7 | 3.172 |
| 16256–2327(AB) | 338.6 | 2.913 | 338.5 | 2.908 | 338.3 | 2.903 | 338.1 | 2.898 | 337.9 | 2.893 |
| 16256–2327(DE) | 259.9 | 0.214 | 253.8 | 0.211 | 247.7 | 0.210 | 241.5 | 0.210 | 235.4 | 0.213 |
4. CONCLUSIONS

We presented here a new method for determination of the orbital parameters of visual binary stars. This method yields to the reliable orbit solution even in the case of a short arc. On the other hand SGS method is fully automated and very easy to use what is specially important when deal with a large amount of data. Thus the method will be useful in future astrometric missions such as SIM\(^3\) and GAIA\(^4\). In order to improve the orbital parameters of visual binaries presented here, new measurements are necessary. The observers should pay the more attention to the star BU 1115 DE which will pass through the periastron at the middle of 2008.

ACKNOWLEDGMENTS. I would like to express my thanks to Dr. J.A.Docobo (reere) and Dr. Z. Cvetković for their useful comments and suggestions. This research have made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory and the Simbad database operated at CDS, Strasbourg, France. This research has been supported by the Ministry of Science of the Republic of Serbia (Project No 146004 "Dynamics of Celestial Bodies, Systems and Populations").

REFERENCES

Aitken R. G. 1906, Lick Obs. Bull. 4, 4
Angelov T. 1993, Bull. Astron. Belgrade, 148, 1
Barton S. G. 1926, AJ, 36, 155

\(^3\)Space Interferometry Mission (SIM), [http://sim.jpl.nasa.gov/](http://sim.jpl.nasa.gov/)
\(^4\)Global Astrometric Interferometer for Astrophysics (GAIA), [http://astro.estec.esa.nl/GAIA/](http://astro.estec.esa.nl/GAIA/)
Orbits Of Five Visual Binary Stars

Burnham S. W. 1894, Publ. Lick Obs. 2, 1
Cvetković Z., Pavlović R., Strigachev A., Novaković B., Popović G. M. 2007, Serb. Astron. J., 174, 83
Docobo J. A. 1985, Celest. Mech., 36, 143
Docobo J. A., Ling J. F., Prieto C., Costa J. M., Costado M. T. and Magdalena P. 2001, Acta Astronomica 51, 353
Donnanget J. 1981, A&A, 94, 45
Eichhorn K. H., Xu Yu-Lin 1990, AJ, 358, 575
ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Hartkopf W. I., McAlister H. A., Franz O. G. 1989, AJ, 98, 1014
Hartkopf W. I., Mason B. D., McAlister H. A. 2000, AJ, 119, 3084
Hartkopf W. I., Mason B. D., Worley C. E. 2001, AJ 122, 3472
Hartkopf W. I., Mason B. D. 2006, Sixth Catalog of Orbits of Visual Binary Stars, US Naval Observatory, Washington. Electronic version [http://ad.usno.navy.mil/wds/orb6.html](http://ad.usno.navy.mil/wds/orb6.html)
Hartkopf W. I., Mason B. D., Wycoff G. L., Kang D. 2006, Catalog of Rectilinear Elements, U.S. Naval Observatory, Washington. Electronic version [http://ad.usno.navy.mil/wds/lin1.html](http://ad.usno.navy.mil/wds/lin1.html)
Heintz W. D. 1969, A&A, 2, 169
Holden E. S. 1884, Publ. Washburn Obs. 2, 97
Mason B. D., Wycoff G. L., Hartkopf W. I. 2006, The Washington Double Star Catalogue, US Naval Observatory, Washington. Electronic version [http://ad.usno.navy.mil/wds/wds.html](http://ad.usno.navy.mil/wds/wds.html)
Novaković B. 2007, Chin. J. Astron. Astrophys. 7, 415
Novaković B. 2007, IAU Commission 26 Inf. Circ., 162
Olević D., Cvetković Z. 2004, A&A, 415, 259
Pourbaix D. 1994, A&A, 290, 682
Press W. H., Teukolsky S. A., Vetterling W. T., Flannery B. P. 1992, in Numerical recipes in Fortran. The art of scientific computing., 2nd ed., Cambridge University Press, New York
Schmidt-Kaler Th. 1982, in: Numerical Data and Functional Relationships in Science and Technology New Series, eds. L. H. Aller, I. Appenzeller, B. Baschek et al., Landolt-Bornstein 2-B, p. 1
Soderhjelm S. 1999, A&A, 341, 121
Thiele T. N. 1883, Astron. Nachr., 104, 245
van den Bos W. H. 1926, Union Circ., 68, 354
van den Bos W. H. 1932, Union Circ., 86, 261