New Double Stars from Asteroidal Occultations, 1971 - 2008

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Abstract: Observations of occultations by asteroids and planetary moons can detect double stars with separations in the range of about 0.3" to 0.001". This paper lists all double stars detected in asteroidal occultations up to the end of 2008. It also provides a general explanation of the observational method and analysis. The incidence of double stars with a separation in the range 0.001" to 0.1" with a magnitude difference less than 2 is estimated to be about 1%.

New Double Stars from Asteroidal Occultations, 1971 - 2008

Introduction

Asteroids and planetary moons will naturally occult many stars as they move through the sky. The biggest challenge in observing such occultations is to accurately predict the time of the occultation event and the location of the shadow path as it crosses the Earth. Since the Hipparcos mission, and the availability of catalogues like Tycho2 and UCAC2, predictions of occultations by asteroids and planetary moons with uncertainties of 100km in the path location have become routine. For the last few years almost 200 occultation events per year have been observed around the world.

In the early days of asteroidal occultations, most observations were made visually. For the last several years the great majority of observations are made using video cameras with a time signal obtained from the GPS satellite system inserted into the video stream. Compared to visual observing, video provides enhanced time resolution, and a record that can be measured to deduce accurate event times. Asteroid profiles can be measured at the 1-km scale using small telescopes and inexpensive video detectors, as has been illustrated by Timerson [1].

In a typical occultation the asteroid is not visible. The occultation is recorded as the sudden disappearance of the star, followed some seconds (or tens of seconds) later with a sudden reappearance of the star. For a small number of events, the occultation may involve:

A partial drop in light, followed by a complete drop in light. The order of the light change may be either the same, or reversed, when the star reappears; or

There is simply a partial drop in light.

These are characteristics of the star being a double star – with the changes of light occurring as the two stars are sequentially hidden by the asteroid. When this occurs, a double star is typically 'discovered'. If there are several observers at spaced locations, it is possible to combine the observations in a way that allows the PA and separation to be solved. The typical measurement accuracy obtained is a milli-arcsec in separation, and a few degrees in PA.

The practical minimum separation detectable by this method is about 1 milli-arcsec – a limit arising from the time resolution of the video cameras being used, and Fresnel diffraction. The maximum separation detectable is limited by the apparent diameter of the asteroid involved. If the diameter is less than the separation, an occultation of only one star might occur – with there being no data to measure the separation from the second star, but these cases usually involve doubles already known from visual or other observations. More detail about the method of analysis is set out in the Appendix.

Results – 1971 to 2008

Double stars have been detected in occultations by asteroids and planetary satellites since 1971. While some of these detections have been published in the literature, almost none are listed in the Interferometric Catalogue or the Washington Double Star catalogue. Table 1 presents the measures of all double stars observed or discovered in these occultations up to the end of 2008 – whether or not they have been reported elsewhere. They include the bright stars γ Gem (HIP 31681), λ Vir (HIP 69974), β^2 Sco (HIP 78821), 1 Vul (HIP 78821) and 16 Psc (HIP 116495). References are given for those events known to have been published in the literature.

At the time these observations were made, little attention was given to determining the star magnitudes. Component magnitudes determined from photoelectric recordings were published for the three events listed below observed before 1983. Most of the other occultations listed were video recorded, but until recently there was no easy way to quantify the magnitudes of the component stars from video recordings. The authors plan to digitize the older video recordings and publish a list of component magnitudes for most of the listed events in a future publication.

There are three types of entries in Table 1:

- **Single-line entry.** The double star solution for these stars is unique and well determined.
- **Single-line entry with a 3-point range** (TYC 5614-00026-1 and HIP 38465). For these stars the data is insufficient to provide a unique solution, but are constrained by the geometry of the event. The values given are the extreme values in PA (where the separation is also greatest) - and the intermediate value of PA where the separation is least. If the asteroid profile is significantly elliptical, the range in PA can be significantly greater than 180 degrees. The values are given in order of increasing PA.
- **Double-line entry** (TYC 1808-00641-1 and HIP 69974). For these stars there are two well-determined solutions. The observations are insufficient to resolve the ambiguity, or associate a formal uncertainty with the solution.

On the night following the occultation of TYC 1879

(Continued on page 91)

New Double Stars from Asteroidal Occultations, 1971 - 2008

Table 1: Double stars discovered or measured in asteroidal occultations: 1971 - 2008

Star number, J2000 RA/Dec WDS/4th Interfer. ID	Position Angle (PA) (degrees)	Angular Separation (masec)	Date	Asteroid	Publ Ref
TYC 0622-00932-1 01 46 51.55 +08 16 08.3 -	248.7 ± 2.5	18.8 ± 1.1	2005 Nov 11 2005.865	116 Sirona	-
TYC 1808-00641-1 03 53 33.26 +27 18 06.1 -	278.1 or 272.1	5.1 or 25.1	2008 Jan 14 2008.034	1258 Sicilia	-
TYC 1879-02151-1 06 31 17.55 +22 47 50.9 COU 581	240.0 ± 0.5	261.9 ± 1.5	2006 Sep 19 2006.715	144 Vibilia	-
TYC 1908-00844-1 07 14 41.22 +29 52 38.7 -	302.9 ± 0.1	170.4 ± 0.3	2006 Nov 29 2006.909	578 Happelia	-
TYC 1947-00293-1 08 25 01.65 +28 33 55.3 -	105.6	106.3	2006 Dec 18 2006.961	87 Sylvia	2
TYC 2411-01645-1 05 31 33.75 +35 01 45.8 -	248.7 ± 0.5	6.3 ± 0.1	1996 Nov 25 1996.899	93 Minerva	-
TYC 2916-02502-1 05 52 44.43 +40 10 45.0 -	70.4 ± 3.9	57.5 ± 2.3	1999 Sep 21 1999.719	375 Ursula	-
TYC 5614-00026-1 15 54 10.20 -09 44 49.8 -	165 - 270 - 36	41.0 - 7.0 - 16.0	2002 May 10 2002.353	638 Moira	-
TYC 6154-00401-1 14 41 45.96 -16 36 09.2 -	81.9 ± 1.4	5.4 ± 0.2	2003 Apr 21 2003.301	210 Isabella	-
HIP 26902 05 42 41.48 +36 08 59.4 -	30.3 ±19.7	1.1 ± 0.3	2005 Dec 1 2005.915	99 Dike	3
HIP 30570 06 25 32.94 +23 19 37.8 MCA 26	344.9 ± 1.3	36.5 ± 3.7	2001 Sep 7 2001.682	9 Metis	4
HIP 31681 06 37 42.70 +16 23 57.3 BUP 90A	126.3 ± 4.7	63.4 ± 1.0	1991 Jan 13 1991.032	381 Myrrha	5
HIP 31694 06 37 51.49 +06 40 59.7 HD 47239	26.1 ± 1.4	45.9 ± 2.1	1978 Dec 11 1978.942	18 Melpomene	6
HIP 32525 06 47 13.67 +16 55 34.9 -	70.9 ± 1.9	9.7 ± 0.3	2007 Mar 28 2007.235	72 Feronia	-
HIP 34452 07 08 30.95 +21 59 09.4 OCC 337;	89.0	39.0	1974 Aug 29 1974.657	Saturn 5 (Rhea)	7
HIP 36189 07 27 09.12 +11 57 18.0 HD 58686	230.7 ± 2.5	12.8 ± 0.5	2003 Mar 23 2003.221	704 Interam- nia	-

Table continued on next page.

Table 1 (continued): Double stars discovered or measured in asteroidal occultations: 1971 - 2008

Star number, J2000 RA/Dec WDS/4th Interfer. ID	Position Angle (PA) (degrees)	Angular Separation (masec)	Date	Asteroid	Publ Ref
HIP 38465 07 52 45.59 +18 49 37.4 HD 64072	342 - 103 - 226	43 - 8 - 52	2002 Dec 24 2002.977	334 Chicago	-
HIP 66446 13 37 15.76 +04 25 03.4 HD 118510	309.3 ± 5.4	19.7 ± 1.5	2001 Mar 15 2001.201	423 Diotima	8
HIP 69974 14 19 06.59 -13 22 15.9 HD 125337	13.0 or 210.0	8.0 or 18.1	2006 Apr 12 2006.277	305 Gordonia	-
HIP 76293 15 35 06.23 -25 06 20.2 HD 138790	81.0 ± 3.3	39.5 ± 2.0	2007 May 18 2007.374	1177 Gonnessia	-
HIP 78821 16 05 26.57 -19 48 06.9 MCA 42 CE	311.6 ± 2.3	98.6 ± 3.0	1971 May 14 1971.363	Jupiter I (Io)	9
HIP 94703 19 16 13.04 +21 23 25.5 HJ 2862 AB	272.0 ±13.6	3.0 ± 0.6	1983 May 29 1983.405	2 Pallas	10
HIP116495 23 36 23.29 +02 06 08.0 THP 1	117.6 ± 5.1	9.8 ± 0.8	2006 May 5 2006.340	7 Iris	11

(Continued from page 89)

-02151-1 Jean Lecacheux measured the pair from Pic-du-Midi observatory, using the 1.05-m reflector at 43-meters focal length and fast CCD imaging. The position angle and separation were measured as 241 deg and 260 masec, which can be compared with the occultation values of 240.0 ± 0.5 deg and 261.9 ± 1.5masec.

Observers

The determination of the double star details from an asteroidal occultation is usually the result of combining the results from all observers who successfully observed the event. The names of the observers for each double star determination are given in Table 2.

A Statistical Observation

Asteroidal occultations will expose a double star if the separation is in the range of 0.001” to 0.l”. There is also a magnitude limitation arising from the brightness of the stars being observed and the equipment being used to record the event; generally, if the magnitude difference is less than 2 magnitudes any component would be expected to be identified in the video recording.

Video observations became the dominant recording technique from about 2002. For the years 2003 to 2008, there have been a total of 1009 observed occultations. Over that period 11 double stars were detected in the occultation. From this it may be inferred that the incidence of double stars with a separation in the range 0.001” to 0.1” with a magnitude difference less than 2 is about 1%.

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(Continued on page 93)

Table 2: Observers for double star determinations.

Star number	Observers
0622-00932-1	T. Farris, M. Good, J. Goss, R. James, D. Snyder, B. Stevens
1808-00641-1	R. Venable
1879-02151-1	L. Blommers, I. Bryukhanov, O. Canales, J. Caquel, R. Casas, E. Frappa, R. Goncalves, A. Klotz, C. Labordena, M. Lavayssiere, J. Lecacheux, C. Perello, J. Ripero, L. Smelcer, S. Sposetti, G. Vaudescal, I. Vinyaminov.
1908-00844-1	M. Castets, F. Colas, O. Dechambre, A. Eberle, O. Farago, J. Lecacheux, M. Meunier
1947-00293-1	King, C. Lin, Lin, Zhang
2411-01645-1	H. Akazawa, N. Ohkura
2916-02502-1	F. Anet, R. Buchheim, J. McCormick, B. Owen, J. Sanford
5614-00026-1	R. Baldrige, D. Dunham, R. Nolthenius, R. Venable
6154-00401-1	A. Gilmore, D. Herald, R. Price, P. Purcell
HIP 26902	D. Dunham, G. Fishkorn, J. Sedlak, W. Warren, J. Wetmore
HIP 30570	D. Dunham, R. Innes, W. Morgan, R. Nolthenius, K. Okasaki, S. Preston
HIP 31681	Y. Ban, S. Fukushima, A. Hagiwara, T. Hasegawa, A. Hashimoto, Y. Hirose, T. Homma, J. Horiuchi, W. Kakei, S. Kaneko, H. Karasaki, T. Kiyokawa, H. Koyama, Y. Moriya, H. Oya, I. Sato, M. Sato, H. Shibuya, K. Shima, M. Soma, Y. Suenaga, M. Sugai, A. Suzuki, K. Tanaka, S. Waku, M. Yamada
HIP 31694	M. A'Hearn, R. Bolster, D. Dunham, J. Dunham, F. Espenak, T. Van Flandern, Schmidt, D. Skillman
HIP 32525	K. Coughlin, R. Fleishman
HIP 34452	M. De Coca, V. De Gaia, A. Quintanilla
HIP 36189	A. Nakanishi, A. Tsuchikawa, A. Yaeza, A. Miyamoto, J. Bedient, B. Brevoort, S. Bus, C. Sakaki, E. Cleintuar, D. Dunham, O. El, W. El, V. Fukunaga, W. Fukunaga, H. Nihei, H. Hamanowa, H. Nagai, H. Sugai, H. Sato, H. Watanabe, I. Ootsuki, K. Kitazaki, K. Usuki, M. Sato, P. Maley, M. Momose, M. Koishikawa, M. Ishida, M. Okamoto, M. Fujita, M. Ida, N. Kita, S. O'Meara, L. Roberts, R. Ikeshita, S. Uehara, S. Kaneko, S. Suzuki, R. Savalle, S. Yoneyama, J. Swatek, R. Sydney, H. Takashima, D. Tholen, Ts. Sato, A. Watanabe, Y. Tonomura, Y. Hirose, Y. Itou, Y. Sugiyama, M. Kouda, H. Yoshida, M. Yokokawa, E. Konno, K. Sasaki, To. Sato, T. Oribe, H. Sugawara, H. Tomioka, A. Kuboniwa
HIP 38465	C. Bader, G. Billings, M. Damashek, R. D'Egidio, D. Dunham, R. Emmons, J. Holtz, A. Lowe, C. Roelle
HIP 66446	G. Akrivas, M. Appakutty, P.M. Berge, M. Bonnet, J. Caquel, F. Colas, P. Gilabert, K. Jayakumar, H. Kulkarni, J. Lecacheux, C. Leyrat, M. Maillard, P. Martinez, A. Paranjpye, J. Piraux, R. Poncy, M. Prabhunne, O. Ruau, M. Senegas, K. Shah, B. Tregon, R. Vasundhara, C. Velu.
HIP 69974	R. Venable
HIP 76293	L. Barak, S. Gebhard, T. Janik, F. Lomoz, J. Manek, Z. Moravec, M. Parl, V. Priban, H. Raab, L. Smid
HIP 78821	Bartholdi, Fallon, Devinney, Oliver, Owen, Smith
HIP 94703	J. Abdias, M. Adams, M. A'Hearn, S. Austin, D. Baker, J. Barton, Bartz, R. Binz, B. Birdsong, B. Blagg, Brady, J. Bragg, J. Breazeale, M. Brewster, D. Brunett, J. Camp, T. Campbell, J. Cannizzo, J. Chauvin, D. Clark, J. Craft, Crawford, J. Culberson, B. Cuthbertson, S. Dale, B. Darnell, C. Davis, L. Dedear, L. Delaney, J. Dellinger, R. Dietz, R. Diiulio, J. Doryk, W. Douglass, D. Dunham, J. Dunham, G. Ellis, S. Elsner, J. Erickson, G. Felos, D. Foster, T. Fox, T. Freeman, M. Frueh, D. Garland, D. Garnet, G. Gonzales, C. Graham, J. Graves, D. Green, Greer, J. Hagan, R. Harper, F. Harvey, N. Henderson, D. Hensch, C. Herold, W. Hoffler, Hok, A. Hradesky, Hubbard, B. Hudgens, S. Ireland, B. Jansen, A. Jon, A. Jones, K. Jurgens, C. Kennedy, R. Kennedy, T. Kenyon, G. Kiser, E. Kolarich, D. Kornbluh, M. Lawson, D. Leblanc, J. Lucke, P. Maley, T. Malone, E. Manual, M. McCants, R. McCormack, C. McDougal, J. McGaha, J. Meadows, G. Metcalf, B. Mitchell, M. Mooney, Moreno, S. Morgan, J. Mote, W. Nissen, R. Nolthenius, D. Oliver, T. Oswalt, G. Page, R. Peters, J. Petersen, H. Povenmire, P. Powell, B. Prislovsky, J. Ratley, L. Reed, A. Reeves, B. Riefer, G. Roark, J. Robicheaux, S. Roby, P. Romig, J. Rose, Rouw, P. Roy, S. Sawyer, D. Schinkevic, G. Schneider, R. Schnurr, J. Schroeder, T. Schult, M. Seslar, W. Settle, C. Sexton, J. Shinner, D. Siner, J. Smith, B. Snow, J. Stafford, H. Stanley, D. Strum, D. Sventek, P. Sventek, Tafliger, R. Taibi, R. Teed, M. Treadway, R. Weber, A. Whipple, T. Williams, R. Wood, L. Woods, Wren, J. Young, G. Zentz, J. Zitwer
HIP116495	R. Boyle, L. Garrett, J. Holtz, M. Kozubal, F. Melillo, B. Thompson

New Double Stars from Asteroidal Occultations, 1971 - 2008

(Continued from page 91)

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Appendix:

Deriving Double Star Measurements from an Asteroidal Occultation

An asteroidal occultation results in the sudden extinction of light from a star as an asteroid passes in front of it. The typical duration of an occultation is a few seconds. A 'good' occultation will last for over 10 seconds; on rare occasions an occultation will last for over a minute. You can visualise an asteroidal occultation by thinking of the shadow of the asteroid cast on the Earth by the star. That shadow will cross the Earth as a result of the asteroid's motion. Typically the shadow will cross the Earth in about 20 minutes, and the path of the shadow will have a width equal to the diameter of the asteroid. An observer within the path can record the shadow passing over them by recording the time at which the star light disappears and reappears. Place several observers across the shadow path, and the occultation times recorded by the observers effectively map out the size and shape of the shadow – and hence of the asteroid. This has been the main motivation for observing asteroidal occultations.

The greatest difficulty with observing asteroidal occultations is accurately predicting the location of the shadow path. For a well-known main belt asteroid, the uncertainty in the path location is rarely less than 50km, and is often well over 100km. For a trans-Neptunian asteroid, the uncertainty is typically thousands of km or larger!

For a small number of events, the occulted star is observed to be a double star. This is typically detected as a two-step change in light level as the occultation starts or ends. For a double star to be detected and measured, the separation cannot be much larger than the apparent diameter of the asteroid. In practice, this means that most double stars discovered in an asteroidal occultation have a separation less than 0.1", and none have been recorded with a separation greater than 0.3". The minimum separation is limited by Fresnel diffraction, and the time resolution of the video cameras used. So far no double star with a separation of less than 1 masec has been identified.

The majority of observations are presently made using low-light video cameras, running at either 30 fps (NTSC) or 25fps (PAL). The vertical synchronisation pulse for each video frame is used to trigger the reading of a GPS-controlled clock, with a corresponding time-stamp being video-inserted near the bottom of that frame. The video recording is analysed using a tool such as Limovie (http://www005.upp.so-net.ne.jp/k_miyash/occ02/limovie_en.html) to extract a timed light curve.

The process for reducing an asteroidal occultation involves the following:

- The process uses the "Fundamental plane". This is a plane through the centre of the Earth that is normal to the *apparent* direction of the star;
- A moving reference frame is defined on that plane – with its motion corresponding to the ephemeris motion of the asteroid's shadow on

New Double Stars from Asteroidal Occultations, 1971 - 2008

the plane. A nominal zero position is arbitrarily defined using one of the observations.

- For each observed event by each observer, the observer's location on the surface of the oblate Earth is projected onto the moving reference frame.

The projection of the observers' locations results in a series of data points in the moving reference frame that represents the outline of the asteroid. Figure 1 is such a plot from an occultation of HIP 36189 by Interamnia on 2003 March 23 – an occultation involving a double star. In this plot, only the events for the primary star are included. (The points in a line at the top and bottom of the plot represent the time of closest approach for observers who recorded no occultation. The direction of motion of the asteroid is normal to these lines.)

Figure 1: Projection of observers' locations from occultation of HIP 36189.

Normal processing of the occultation observations entails a least-squares fitting of an ellipse to the data points. The least-squares solution involves 5 unknowns – the X and Y coordinates of the centre of the ellipse, the major and minor axes of the ellipse, and the orientation of the ellipse.

When a double star is involved, the effect is to create a second set of data points that is displaced from the first set. Importantly, the shadow of the asteroid cast by the companion star will have the same size, shape and orientation as the shadow cast by the primary star – it will merely be displaced from the main shadow by an amount dependent upon the separation, and in a direction dependent upon the PA of the companion. As a result, the double star solution *merely* requires solving for two additional unknowns - the separation and position angle that will bring the two shadow profiles into mutual alignment.

In Figures 2 - 4, Figure 2 shows the data points corresponding to the secondary star. Figure 3 has the data points of both the primary and secondary stars plotted together, with no offset. Figure 4 has the data points offset so that the two profiles are in full alignment. The offset is indicated by the double star representation in the centre of the plot, which is drawn at the scale of the asteroid. In this case, the apparent diameter of Interamnia was 0.177", and the measured separation of the stars was 12.8masec. The duration of the occultation was up to 71 seconds, with the time

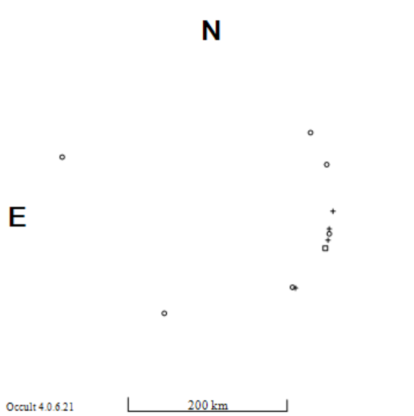

Figure 2: Data points corresponding to the secondary star.

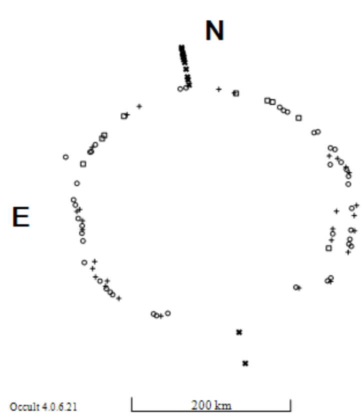

Figure 3: Data points for both stars with no offset.

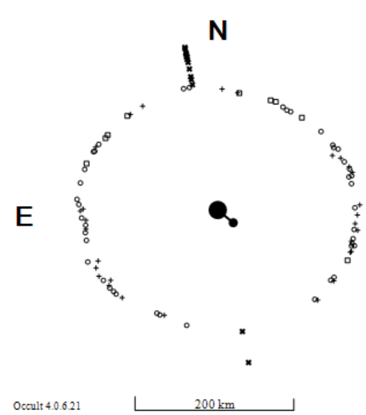

Figure 4: Data points for both stars with offset so that profiles are aligned.

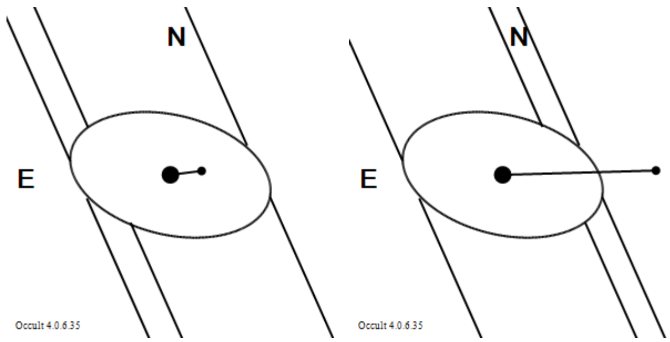

Figure 5: Illustration of possible amibiguity if only one observer records double star events.

difference between the two components being up to 9 seconds.

Where the occultation is well observed with several chords, and the double star is recorded at both the disappearance and reappearance events, the solution for the separation and position angle can have very high precision.

If only one of several observers records double star events, the solution may have an ambiguity. In such circumstances the observed chord might fit on both sides of the asteroid – leading to two solutions for the separation and position angle. This is illustrated by the following two diagrams (Figure 5), which relate to the occultation of TYC 1808-00641-1. Two observers (actually for this event, one observer running two widely-separated stations, with video techniques making it possible to run separate stations remotely) recorded the occultation of the main star – with chords being near the extremities of the asteroid. One of those stations (the left-most in the diagram) also recorded an occultation by a secondary star. As shown in the diagrams, there are two possible locations where the observed chord of the secondary matches the profile of the asteroid – leading to two possible solutions for separation and PA, as indicated by the double star representation in each diagram. In this case both solutions have a similar PA. However in general the two PAs can differ by up to 180 deg. Note that one of the solutions can be excluded if it is clear that stations that 'should have' recorded the second star occulted under that solution definitely did not see that star occulted.

When there is a large magnitude difference between the stars, it may be that the companion star is detected at only one of the disappearance and reappearance events. If there are several spaced observers who record the companion star, a reliable unique solution can still be obtained. However if only one observer (or two closely spaced observers) record the companion, a unique solution is not possible. Rather there will be a range of possible solutions extending over a range of position angles of about 180 degrees. The following diagrams (Figure 6) are for the occultation of HIP 38465. The first diagram shows the outline of the asteroid as determined by nine observers. One observer detected a step event on the reappearance (in the diagram, the star is moving from right to left). The location of the star path is constrained by the diameter of the asteroid. The 2nd diagram shows the solution for the secondary star assuming its chord is at its maximum position north. The fourth diagram is for the chord being at the maximum position south, and the third diagram is the solution for minimum separation of the components.

The situation differs from a single lunar occultation with a vector separation in three ways:

1. For a lunar observation the range of possible PA values is 180°. For an asteroidal observation the possi-

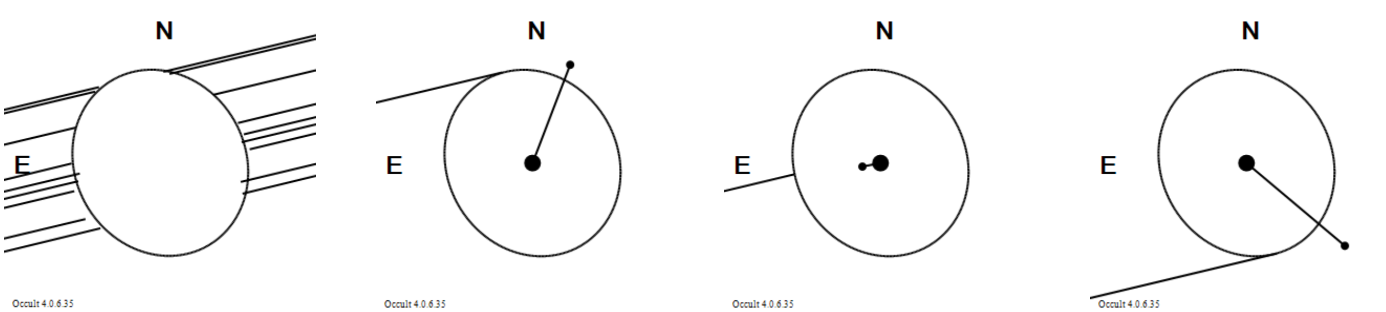

Figure 6: Possible amibiguities in separation and position angle if only one observer sees the secondary as a step event in the light curve. See text.

New Double Stars from Asteroidal Occultations, 1971 - 2008

ble range of PA is usually greater than 180°. (In this case, it is 244°)

2. In a lunar observation, no limit on the separation can be derived from a single observation. In an asteroidal occultation the diameter of the asteroid imposes an upper limit on the separation. In this case it is 0.052" – assuming the solution of the fourth diagram.

3. In a lunar occultation the separation is related to the difference between the PA of the star components and of the occultation vector by a simple secant relationship. For an asteroidal occultation the relationship is more complex, and depends upon the shape of the asteroid.

These are illustrated in the following plot of the separation against position angle for this star, together with a plot of the separation curve for an equivalent lunar occultation, Figure 7. As can be seen, the lunar solution is symmetric, and is asymptotic at 90° from the central location (of 105°). In contrast the asteroid solution is asymmetric, has no asymptotes, but has limiting values of PA with corresponding maximum values of separation.

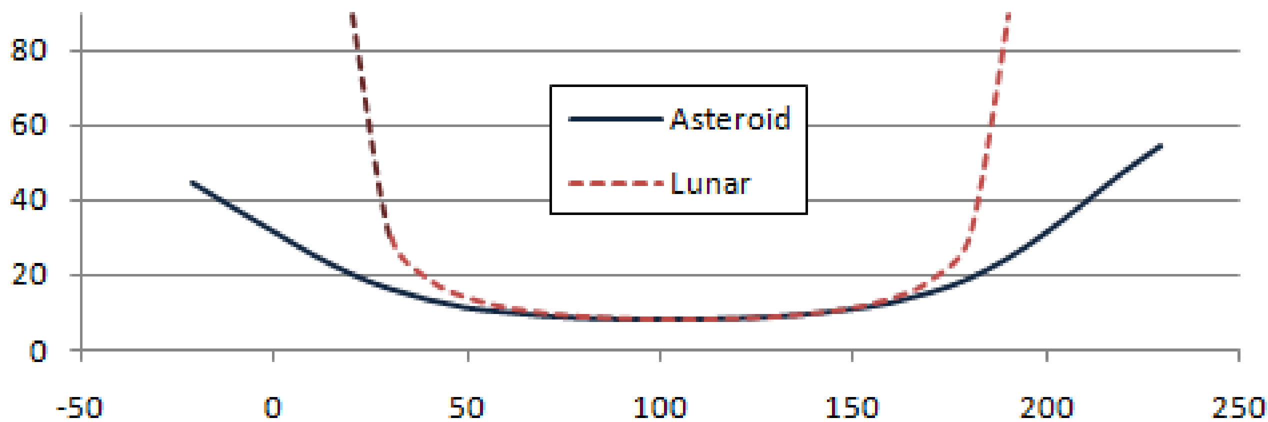

Figure 7: Separation versus position angle for a double star for both lunar and asteroidal occultations.