Zum raum wird hier die Zeit (Time here becomes space) - Parsifal, Act I

The first edition of this volume appeared in 2004. Since then, interest in visual double star observation has increased considerably and there are now several very active groups around the world. I have taken the opportunity to revise the first edition and remove some typos and also to add four new chapters which I believe reflects the increased activity.

I am grateful to Springer for the chance to revise this book.

Double stars are the rule, rather than the exception, in the solar neighbourhood and probably beyond. Current theories of star formation point to multiple stars or stars and planets as the preferential outcome of gravitating protostellar material. Stellar pairs can be detected at many wavelengths from X-rays, where modern satellites can resolve the two brightest components of Castor (separation 3.8 arc seconds) to the radio where the precision of long baseline interferometry can also see the 4 milli-arsecond ‘wobble? in the 2.87 day eclipsing system of Algol and can distinguish which of the two stars is emitting the radio waves. They come in a wide range of orbital sizes, periods and masses. From the multiple system alpha + KU Lib where the stars are separated by almost one parsec and whose motion is barely perceptible, through the spectroscopic binaries with periods of weeks, down to exotic pairs like double white dwarf contact systems with periods of 5 minutes. From young x-star binaries like NGC 3603 A1 in the Large Magellanic Cloud containing two extremely bright and hot stars, of 116 and 89 solar masses, down to the snappily named 2MASS J1426316+155701 a pair of brown dwarfs with masses only 0.074 and 0.066 times that of the Sun.

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I'm extremely grateful to my colleagues who have contributed their expertise so willingly in the chapters within: Andreas Alzner, Rainer Anton, Graham Appleby, Erno Berko, Owen Brazell, Bob Buchheim, Rafael Caballero, James Daley, Michael Greaney, Andreas Maurer, Jeremy Perez, Michael Ropolewski, Christopher Taylor, Tom Teague, and Nils Turner. I also thank Andreas Alzner, and Jean-François Courtot for help in proof-reading. Needless to say, mine is the final responsibility for any errors which might escape the various proof-reading exercises.

I also thank Gyorgi Vaskuti, Florent Losse, Rene Gili for up-to-date informqation on double star observation programmes in Hungary and France.

My thanks are also due to Patrick Moore who first suggested the idea of this volume and John Watson, Springer's Managing Editor who has been very supportive throughout the whole process.

Finally my wife Angela has not only had to contend with many hours of my sitting in front of the computer but has actively encouraged me to 'get the thing finished'.

Robert Argyle, Waterbeach, Cambridgeshire 2011 March

Nothing here at present

Contents

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Separation (AU)	0.01	<1	10	50	100	1000	10000
Angular separation	$<0''.001$		$0''.01$	$0''.02$-$0''.03$		1	>1

Binary type

Eclipsing
Spectroscopic
Interferometric
close visual wide visual

Observation methods
Spectroscopy
Speckle
Coronography/adaptive optics
Direct imaging

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Chapter 1
More than one Sun

1.1 Introduction

On a clear, dark night several thousand stars can be seen at any one time. They form familiar patterns such as the Great Bear and Cygnus in the northern hemisphere and Scorpio and Crux in the south. The distances are so great that we see the constellation patterns essentially unchanged from those seen by the Ancient Egyptians for instance. This is partly due to the fact that some of the bright stars in constellations are in what are called moving groups - a loose association of stars moving through space together. More tightly bound are clusters of star such as the Pleiades or 7 Sisters which appears in the northern sky in the late summer. Eventually the moving groups and clusters of stars will gradually disperse because the distance between the stars is such that the gravitational attraction between the members is relatively weak.

Those with keen eyes will be able to see some close pairs of stars without optical aid. The most famous is Mizar and Alcor in the tail of the Great Bear. The first recorded 'naked-eye' pair is ? Sgr which was mentioned by Claudius Ptolemy in his famous Almagest catalogue of circa 140 AD. It is described (1) as 'The star in the middle of the eye (of Sagittarius) which is nebulous and double'. The angular separation of this pair is 13 arc minutes, or about the same separation as Mizar and Alcor. As a comparison, the apparent diameter of the Full Moon is 30 arc minutes.

1.2 Relative positions in visual double stars

The separation is one of two quantities needed to fully describe the relative position of double stars, the other being the position angle. With the brighter of the two stars being taken as the origin, the separation is defined as the angular distance in arc seconds between the two stars and the position angle is the bearing of the fainter star from the brighter in degrees with north being taken as 0 degrees, E is 90 degrees and so on (Fig 1.1a shows the situation for the naked eye and binoculars). When a telescope is used the view is inverted so Fig 1.1b applies to telescopic views.)

Fig 1.1a Naked eye and binoculars Fig 1.1b Telescopic view

It is usual to represent separation by the Greek letter rho (ρ) and position angle by the Greek letter theta (θ). These terms will be used throughout this book. Another common term is Δm which is shorthand for difference of magnitude between the primary and secondary stars. Unless otherwise stated the magnitudes in this book will be visual. The fainter of the two stars is sometimes called the comes, a Latin word meaning companion.

1.3 Naked eye limits

In the case of the human eye, the closest pair of stars which can be seen unaided depends on the diameter of the pupil. This, in turn, depends on the lighting conditions and when fully dark-adapted the pupil may be 6 or 7mm in diameter, suggesting that the limit of resolution from the Airy formula (see Chapter 10) is about 20 arc seconds but the presence of aberrations in the eye and the low light levels from the night sky conspire to reduce the effective resolution to about 2.5 arc minutes.

In practice a normal pair of eyes should be able to see the stars θ^1 and θ^2 Tauri at 5.5 arc minutes without difficulty and some may be able to make out ε^1 and ε^2 Lyrae at 3.6 arc minutes, greatly. Ability to resolve naked-eye pairs tends to deteriorate with age and younger eyes will probably do better, although practice undoubtedly enhances keenness of vision. Sight, like hearing, or any of the five senses, can be improved with experience .Table 1 contains a short list of bright wide, pairs which, it is suggested, can be used as a test of naked eye resolving power. In some of the cases, both stars have a Bayer letter or Flamsteed number and these are used as the main identifier. The positions are given for equinox 2000.0 followed by the date of the most recent measure, the visual magnitudes of both stars and the position angle and separation of the pair. Most of these pairs are the results of chance alignment.

1.4 Optical pairs

Optical double stars are simply formed due to line-of-sight coincidence. They are usually widely separated ($>$ 5 arc seconds or so) and the proper motions, or the individual motions in right ascension and declination, of each component, across the sky, are significantly different. In addition, the stars are usually unequally bright reflecting the difference in distances but this by itself is not a criterion. A good example is δ Herculis where the two stars were separated more than $34''$ at discovery by the elder Herschel in 1779, they closed up to about $8''.8$ in 1964 and are now at $12''$ and widening (Fig 1.2a). Such pairs are usually of no direct scientific interest to astronomers but can produce some fine sights in small telescopes. The stars in δ

Herculis are, for instance, pale yellow and blue in colour and the primary is about 24 parsecs distant. Little is known about the companion.

Fig 1.2a The proper motion of δ Herculis. Measurements of the position angle and separation of star B with respect to A over many years shows the relative motion between the two. Fig 1.2b shows the real situation with star A moving towards PA 187° at a rate of $0''.159$ per year whilst B moves towards PA 275° by $0''.117$ per year.

Table 1.1 Some naked-eye double stars

RA 2000 Dec 2000	Pair	Epoch	PA (°)	Sep (″)	Va	Vb
0318.2 -6230	ζ Ret	2003	217	309.2	5.24	5.33
0425.4 +2218	κ Tau	2002	174	339.7	4.21	5.27
0428.7 +1552	θ Tau	2002	348	336.7	3.40	3.84
0439.3 +1555	σ Tau	2008	194	436.3	4.67	5.08
0718.3 -3644	Jc 10 Pup	1997	98	240.1	4.65	5.11
1208.4 -5043	δ Cen	1999	325	269.1	2.58	4.46
1450.9 -1603	α Lib	2002	315	231.1	2.75	5.15
1622.4 +3348	ν CrB	1998	164	360.8	5.20	5.39
1844.3 +3940	ε Lyr	2009	172	219.2	4.59	4.67
1928.7 +2440	6 -8 Vul	2008	28	427.3	4.44	5.82
2013.6 +4644	31+32 Cyg	2008	325	333.8	3.80	4.80
2018.1 -1233	α Cap	2002	292	381.2	3.80	4.20

1.5 Telescopic pairs

Whilst binoculars, particularly the image-stabilised variety (see Chapter 3) can show literally hundreds of double stars the use of a small telescope will considerably increase the number of pairs of stars that can be seen. It also allows the user to see stellar colours more easily. In a 90-mm telescope, most of the closest pairs than can be seen are binary pairs - the two stars are physically connected by a mutual gravitational bond - and they rotate around the common centre of gravity in periods ranging from a few tens to a few millions of years.

1.6 Binary stars

1.6.1 Visual binaries

In the case of physically connected pairs of stars what the observer sees when he plots the position angle and separation of the pair over a number of years is a curve.

If followed for the whole orbital period the result would be an ellipse - this is the apparent orbit, in other words, the projection of the true orbit onto the plane of the sky. With a small telescope, hundreds of binary stars can be observed and of these the more nearby pairs offer the best chance of seeing the orbital motion over a few years. Estimates of separation can be made in terms of the diameter of the apparent disk of the brighter component which can be calculated for any telescope aperture using the Airy formula in Chapter 10. Position angle can be estimated to perhaps the nearest 5 or 10 degrees by eye by allowing the pair in question to drift through the field at high magnification with the driving motor stopped.

True (and apparent) orbits come in all shapes and sizes from circular to elongated ellipse but the tilt of the orbital plane can also vary from 90 degrees (in which the plane is in the line of sight) to 0 degrees in which we see the orbit face-on. To describe the real orbit fully requires 7 quantities of which eccentricity and inclination have just been explained. In the ellipse, the time at which the two stars are closest is called periastron (similar to perihelion when the Earth is nearest the Sun). The other values are the orbital period in years (the time taken between successive arrivals by star B at the periastron point and three values which describe the size and orientation of the orbit which are described fully in Chapter 7. The motion of star B around A follows Kepler's Laws and in an exact analogy with the solar system, the mass of both stars is related to the size of the orbit and the orbital period.

Fig 1.3a The visual binary 12 Lyncis. p = 706 years, e = 0.03 and orbit inclined at 2° to the plane of the sky. Fig 1.3b - γ Virginis, P = 169 years, eccentricity = 0.89, inclined at 32° to the plane of the sky. The radius of the central circle indicates the Dawes limit for a 20-cm aperture. 12 Lyncis is therefore always visible in this aperture. γ Virginis closed to less than $0''.4$ in early 2005 but is now widening rapidly and will need only 8 to 10-cm for the forseeable future.

Fig. 1.3 gives an example of two well-known visual binaries. Contrast the orbital motion in both pairs by comparing the positions at 1950, 2000 and 2050.

To measure the total mass of both stars requires the apparent orbit to be defined as accurately as possible. This can be done by measuring ρ and θ at different times, for as much of the orbit as is practical. (Long periods will mean that only a preliminary orbit can be obtained). There are measuring techniques of various kinds which can be employed to accurately measure the relative position of B and to determine the values of ρ and θ. Later in this book the various methods that are available to the observer are mentioned in more detail.

For visual binaries, observations of the apparent orbit leads to the determination of the true orbit from which we can derive the sum of the masses, in terms of the solar mass, provided that the parallax is known. The astrometric satellite Hipparcos has been instrumental in providing parallaxes of high accuracy for a large number of binary stars.

Once we know the apparent orbit of a visual binary, we can, if the parallax of the system is also known, obtain the sum of the masses of the stars in the system via Kepler's third law:

where a is the semi-major axis of the apparent ellipse, and π is the parallax. Both are in arc seconds and P is in years. The mass sum is then given in units of the sun's mass.

To obtain the individual masses requires defining the apparent orbit for each component by measuring its position with time against the background field stars. The apparent orbits are identical with the relative sizes determining the ratio of the masses, the primary star being the most massive, traces out the smaller ellipse (see Fig 7.1). Unfortunately this method only applies to a small number of wide, nearby pairs which can be resolved photographically throughout the orbit.

Combining (1.1) and (1.2) allows us to get the mass of each component.

The USNO 6th Catalogue of Orbits(2) contains more than 1,xxx orbits of which 1,xxx refer to pairs resolvable by conventional techniques. Of these orbits, about 4grade 1, the longest period being that of 70 Oph at 88.38 years. Table 1 shows the distribution of the 5 main orbit grades (Sept 2010). Throughout this volume reference will be made to the 5th and 6th editions of this catalogue. The 5th edition is available from the USNO on CD-ROM ? (see the appendix) whilst the 6th is the dynamic version which is regularly updated but a copy of this version appears on the CD-ROM accompanying this book.

Table 1.2 Distribution of orbit quality in the USNO Sixth Orbit Catalogue

Grade Category	Longest period	No. pairs	% of catalogue
Definitive	88.38	61	3.6
Good	206	238	14.1
Reliable	540	370	21.9
Preliminary	4277	527	31.1
Indeterminate	6675	497	29.3

1.6.2 Spectroscopic binaries

These are stars which appear single in all telescopes but turn a spectroscope on them and the spectral lines are observed to shift periodically with time due to the Doppler shift as the stars approach and then recede from the observer. The lines merge when the stars are both moving across the line of sight. There are two main types. When the stars are of similar brightness then two sets of spectral lines can be seen particularly when one star is moving towards us and the other is moving away. These are called double-lined systems. When one star is much brighter than the other then only the spectral lines the bright star can be seen to move periodically. This is called a single-lined system. Spectroscopic binaries have periods ranging from hours to a few tens of years. In a few rare cases they can also be resolved using speckle or ground -based interferometry. Such systems are important as they allow many characteristics of the component stars to be determined.

1.6.3 Astrometric binaries

Again, these are single objects in all telescopes but reveal their duplicity by the effect that the unseen companion star has on the proper motion or the transverse motion of the star against the background of fainter stars. This motion will be constant for a single star but the presence of a companion constantly pulls on the primary star and the effect is to observe the star ‘wobble‘ across the sky . This was first noticed by Bessel in the proper motion of Sirius - some 3.7 arc seconds every year and large enough to be seen by regular measurement with respect to the neighbouring stars. Bessel rightly attributed the periodic wobble of Sirius to the presence of an invisible but massive companion. In 1862 Alvan Clark saw Sirius B for the first time thus confirming Bessel’s prediction.

1.7 Multiple stars

Less common in the telescope, but more spectacular and worth seeking out are the multiple stars. Systems like β Mon, with its 3 pure-white gems within 7 arc seconds, ζ Cancri, of which more later, and ι Cas (yellowish, bluish and bluish, according to Robert Burnham).

If multiple stars are to be stable over a long timescale then they need to follow a certain hierarchy. In the case of a single star orbiting a close pair, the ratio of the orbital periods of the outer star around AB to that of the inner orbit AB is usually at least 10:1. This appears to apply from periods of about 10 days up to thousand of years.

Quadruple stars, of which the most famous is the ’double-double’, epsilon Lyrae can be ordered in two ways. Firstly, as in epsilon’s case, there are two pairs each orbiting the common centre of gravity. Alternatively, a double star is orbited by a distant 3rd star and then even more distantly a fourth star circles the whole group.

Systems of higher multiplicity are known - perhaps the most famous is the sextuple system Castor, which is described in more detail in Chapter 9. A recent catalogue of multiple stars(3) lists 626 triples, 141 quadruples, 28 quintuples and 10 sextuples. The existence of two systems thought to be septuple (? Scorpii and AR Cas) awaits confirmation of further suspected components.

The Trapezium, which to a small telescope user is four stars embedded in the Orion Nebula, is the prototype of another sort of multiple star. It is not strictly ordered like the quadruples such as epsilon Lyrae, but is more a loose aggregation and can be regarded more as a small star cluster than a multiple star as such. It is not any the less beautiful for this and seen against the glowing green background of the nebula, on a cold winter's night in a good telescope it is one of the sky's most spectacular sights.

1.8 History of double star observation

In 1610 the invention of the telescope by Galileo gradually led to the discovery of telescopic double stars but these were noted merely by the way. In 1617 Castelli found that Mizar was itself double(4) and he later added a few more pairs. In 1664 Robert Hooke was observing the comet discovered by Hevelius when he came across γ Arietis, a pair of pure-white stars of the 4th magnitude separated by some 8 arc seconds.

Table 1.3 The first ten telescopic double star discoveries

Pair	Discovery	By
ζ UMa	1617 Jan	Castelli
β Mon	1617 Jan 30	Castelli
θ Orionis ABC	1617 Feb	Galileo
β Sco	1627	Castelli
γ Ari	1664	Hooke
Castor	1678?	G. D. Cassini?
ζCnc AB-C	1680 Mar 22	Flamsteed
α Crucis	1685	Fontenay
α Centauri	1689	Richaud
γ Virginis	1718	Bradley

Over the next one hundred years or so a few more double stars were noted but not catalogued in any determined manner, but this was to change when the Reverend John Michell first suggested that double stars were not merely a line-of-sight effect but that the two components really revolved around each other under a mutual gravitational influence, implying that Newton's Laws applied to objects outside the Solar System. In Philosophical Transactions for 1767, Michell says " ... it is highly probable in particular, and next to a certainty in general, that such double stars, &c, as appear to consist of two or more stars placed close together, do really consist of stars placed near together, and under the influence of some general law, whenever the probability is very great, that there would not have been any such stars near together, if all those that are not less bright than themselves had been scattered at random throughout the whole heavens".

A small catalogue of double stars was compiled in 1780 by Christian Mayer of Mannheim (5) but the next great step was taken by William Herschel who turned his unprecedently powerful telescopes on many bright stars to find that even at high power, some stars appeared as very close pairs. In an attempt to measure stellar parallax, Herschel argued that in unequally bright, close pairs by measuring the position of the faint (hence distant and fixed) star with respect to the bright (or nearby) star he should be able to measure the parallactic shift and hence the distance of the latter. This idea he attributes to Galileo. To prove this he used filar micrometers of his own construction to measure the position of the fainter star with respect to the brighter. However, instead of seeing a 6 monthly ’wobble’ in the position of the bright star with respect to the faint, Herschel found that the relative motion between the two stars was curved and could only be explained if the stars were revolving around a common centre-of-gravity. He had proved that binary stars existed but the mathematical confirmation came six years after his death, in 1828, when the French scientist Savary used the pair ξ UMa (which Herschel had discovered) to show that the apparent orbit of the fainter star around the brighter (assuming the latter was fixed) was an ellipse.

The significance of this work was that it gave an estimate for the ratio of the stellar masses in a binary star system. This resulted in a great impetus in the visual observation of double stars and over the next 50 years or so many rich amateur astronomers in Europe dedicated time and money to making micrometric measurements, or paying someone to do it for them. Dawes, in England, and particularly Baron Ercole Dembowski, in Italy, and others flourished but without the excitement of discovery the work lost momentum and became largely unfashionable by the turn of the century.

In 1857 when Bond first imaged Mizar with the Harvard 15-inch refractor the advantages of photography for double star astronomy were not immediately realised, partly because the resolution obtained initially did not allow much work to be done in the orbital pairs of relatively short period. For those bright pairs where the separation was such that both components could be imaged at all parts of the orbital cycle such as 70 Oph, it was possible to determine individual masses from the size of the apparent ellipses that each star traced out against the stellar background. It was not until the middle of the last century that observers such as Willem Luyten, Peter van de Kamp and Wulff Heintz used photography much more purposefully. Luyten, in a long career, found many pairs of stars with common proper motion, indicative of orbital pairs but with a long period. van de Kamp concentrated on those systems where the only evidence of duplicity was a periodic wobble of a bright star with respect to the background, indicating a faint and close but nonetheless significantly massive companion star.

1.9 The Great Era of Discovery

From 1870 or so when the American astronomer S. W. Burnham first started in double star astronomy a golden period for discovery opened up and continued for about 80 years, first in the northern hemisphere and latterly in the south. The largest refractors in existence were used in systematic surveys of the BD star catalogues by R. G. Aitken and W. J. Hussey in California (they discovered 4,700 pairs between them) and some years later by R. T. A. Innes, W.H. van den Bos and W. S. Finsen at the Republic Observatory, Johannesburg (5,000 discoveries) and Rossiter and colleagues at the Lamont-Hussey Observatory at Bloemfontein (7,650 discoveries) in South Africa. When the latter retired in 1952 it was not long before P. Couteau and P. Muller in France began to search for new pairs again, dividing up the northern heavens with Couteau tackling the zones from $+17^\circ$ to $+52^\circ$ and Muller surveyed the zones near the north pole. They were remarkably successful and Couteau's list now exceeds 2700 new pairs whilst Muller found more than 700. Additionally, W. D. Heintz found 900 new pairs, most of them in a zone close to the equator and in the southern hemisphere.

1.10 Modern techniques

Although it was proposed by Albert Michelson almost a hundred years ago, stellar interferometry is today even more important as a means of researching the dynamics of binary stars as it was then. Michelson's idea led to the construction of an interferometer for the 100-inch reflector on Mount Wilson in the 1920's, consisting of a 20-foot structure with flat mirrors at each end mounted at the top end of the telescope tube.

This instrument uses the interference of light to determine whether a bright single star is either extended i.e. its diameter is resolvable at the Earth or a close double. By combining the light from each of the two small mirrors and adjusting the separation of the mirrors until the fringes thus formed combined in such a way that they cancelled each other out then the separation of the two components could be found from the separation and the position angle from orientation of the fringes. With so little light available only bright stars could be measured.

In 1925 Frederick Pease(6) first resolved Mizar A using this equipment. It was also used for observations of extended sources such as the red supergiant Betelgeuse meant that the diameter of the star could be determined. Other stars measured included the binary system Capella which turned out to have a separation of between 0.03 and 0.05 arc seconds and a period of 104 days.

In the 1970's double star observation underwent a revolution with the invention of speckle interferometry (see Chapter xx). This technique effectively removes the effect of the atmosphere and allows telescopes to operate to the diffraction limit. In the case of the 4-metre reflectors on which it was used, this corresponded to about $0''.025$ or about 4 times closer that Burnham or Aitken could measure. In addition the accuracy of this method was much greater than visual measures and since then it has proved its worth by discovering new very close and rapid binaries and improving the older visual orbits.

The launch of the Hipparcos satellite in 1989 also heralded a new era of double star discovery. Operating high above the atmosphere its slit detectors found some 15,000 new pairs, most of which are difficult objects for small telescopes but a number have already been picked up in very small apertures.

1.11 The Future

Where does double-star observation go next? In the immediate future it will be from the ground where a number of specially-built optical arrays will be operating over the next few years.

At Cambridge in the UK, the COAST (Cambridge Optical Aperture Synthesis Telescope) 5 mirror interferometer has been working for some years with a current baseline of 48 metres and plans to extend this to 100 metres. This is an extension of the Michelson instrument at Mount Wilson. By using more mirrors and using the Earth's spin to rotate the instrument with respect to the star astronomers have used phase closure, a technique first used in radio astronomy, to effectively image the structure of stars such as Betelgeuse.

COAST has easily resolved the bright spectroscopic binary Capella, whose components are about 50 mas apart. Another such instrument, the NPOI (Navy Prototype Optical Interferometer) using 50 metre baselines in Arizona has resolved spectroscopic binaries such as the brighter component of Mizar. Long-known to have a period of 20.5 days, the NPOI can detect and measure the individual stars even though at closest approach they are only 4 milliarcseconds (mas) apart (see Fig 9.1). The combination of the NPOI data and the spectroscopic data can give very accurate values for the size of the orbit, the parallax of the system and the individual masses, and radii of each component.

The CHARA Array is a six-element, optical/IR interferometer located on Mount Wilson, in Southern California. Baselines range from 34 meters all the way to 330 meters. Currently, there are four beam combiner instruments working in the IR: 1) CHARA Classic, a two-beam, open-air combiner working at H and K', having an ultimate sensitivity of about 8.5 magnitudes at K'; 2) CLIMB, a three-beam, open-air combiner working at H and K', having an ultimate sensitivity of about 7.5 magnitudes at K', and capable of measuring 3 baseline visibilities and one phase closure in a single observation; 3) FLUOR, a two-beam, fiber-injection beam combiner working at K', having an ultimate sensitivity of about 5 magnitudes at K'; and 4) MIRC, a four-beam (soon to be six-beam) combiner working at H, having an ultimate sensitivity of 4.5 magnitudes at H, and capable of measuring six baseline visibilities (soon to be 15) and three independent phase closure measurements (soon to be 10) in a single data sample. Also, there are two beam combiner instruments working in the visible: 1) VEGA, a four-beam combiner working at H-alpha (656nm), having an ultimate sensitivity of 6 magnitudes at V in the coarsest resolution, and capable of measuring six baseline visibilities and three independent phase closure measurements in a single data sample; and 2) PAVO, a three-beam combiner working at R and I, having an ultimate sensitivity of 8.5 magnitudes at R, and capable of measuring three baseline visibilities and a single phase closure in a single observation. We are in the process of commissioning CHAMP, a six-way, K-band fringe tracker for MIRC which will increase the sensitivity of MIRC by about 3 magnitudes. CLIMB can also be used to track fringes for VEGA and PAVO, which, while not increasing sensitivity that much, can decrease significantly the amount of time required for observation.

SUSI (Sydney University Stellar Interferometer is located 20 km west of Narrabri in New South Wales, the site of an earlier experiment in intensity interferometry by Hanbury Brown and Twiss. The present instrument is oprating at 160 metre baselines but hardware is planned to expand this to 640 metres in future. The re is a PAVO beam combiner similar to that used at CHARA and it is expected to rach magnitude 7 in 10 wavelength cahnnels simultaneously. Recent papers have dealt with the orbit and masses of the binary star delta Scorpii and observations of the pulsations of the Cepheid I car.

A most eagerly anticpated development will be the use of the 4 VLT telescopes as an interfermometric array. In the meantine the three auxiliary 1.8-metre outrider telescopes have been combined to yield information on stellar shapes and binary orbits. A recent serendipitous observation of sigma Puppis (HD 59717) revealed the spectroscopic binary companion which eclipses the K5III primary every 258 days. The companion which is 5 magnitudes fainter was found 11 mas distant.

Keck

Combining the two 10-metre telescopes has been

Peter Lawson's website(7) covers all the current interferometer projects and has links to the historical ones.

The greatest contribution to the discivery of new binary stars will come from space. The GAIA mission, which is not due to fly until about 201x is expected to find tens of millions of new double stars. For the resolved pairs, the magnitude difference is important. Equally bright pairs (¡15th mag) will probably be (completely resolved at 10 mas, while a 20th magnitude companion would be seen only at some 50 mas. Closer pairs will be observed by their photocentres, but in the 'favourable' period-range 1-10 years, a large proportion of them will have their astrometric orbits determined. This will be possible for photocentric orbit-sizes below 1mas, at least for the brighter systems. Bright (again $<$15th mag.) shorter-period systems (days/months) will be observed by the radial-velocity instrument (at 0.1 mas separation), and millions of (mainly even shorter-period) eclipsing binaries will be observed photometrically.

1.12 References

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Chapter 2
Why observe double stars?

Bob Argyle

2.1 Introduction

Like many branches of astronomy, the observation of double stars can be appreciated at several levels. For those who enjoy the night sky, double stars offer some of the most attractive sights around and they are particularly good in small telescopes where the colours are much more obvious. For a good list of the most impressive pairs, consult the list of 100 best pairs on the Astronomical League Double Star Club website (1) or lists of pairs in Sky & Telescope and other journals (2-8).

Some observers use double stars as a test object to see what their telescope is capable of in terms of angular resolution. Tables 2.1 to 2.6 below give a range of test pairs for both binoculars and telescopes with a range of apertures from 9-cm to 60-cm.

A few observers, find double stars to be so endlessly fascinating that they wish to make to useful contributions to the subject. This may be by making measures of ρ and θ for the binary systems using a micrometer, doing photometry of wider pairs with a CCD camera or calculating orbits from the observed positions. The majority of this book will be dedicated to the description of such techniques and opportunities for useful work are discussed further in Chapter 19.

2.2 Colours

Much has been written on this subject and it will continue to exercise fascination amongst observers. It is perhaps the most compelling reason why people observe double stars. Although watching the stars swing around their huge orbits over the years can also be interesting, it does not strike with the same immediacy.

Here some optical aid makes all the difference. With the naked-eye few colours can be ascertained. The contrast between the reddish-orange Betelgeuse and the white Rigel in Orion can be seen and the deep red of Antares certainly stands out but none of the more subtle colours visible in telescopes appear. Colours tend to be much easier to see when some optical aid is used for a number of reasons. Firstly, there is more light incident on the eye, and the cones which are small receptors in the eye which detect colour, can be more easily stimulated. Next, if the telescope is then deliberately defocussed, the star colours become more prominent. The reason for this appears to be psychological in origin. Thirdly, star colours become more intense when contrasted with other stars of different hues. In some double stars such as iota Cancri the companion (distant 30 arc seconds) appears blue alongside the orange-yellow of the primary star. Yet the spectral types of G7 and A3 indicate that the secondary star should be white and it is simply the contrast with the primary which gives the star its blue colour. In alpha Herculis, the companion which is less than 5 arc seconds away is distinctly green although no single stars of this colour are known to exist. (Some observers have reported that Beta Librae is green or pale green but Robert Burnham who mentions this in his Handbook, states that the star is white). It might be interesting to see how the contrast effect varies as the distance between the two stars in a double star system, for stars of similarly different spectral types and brightnesses.

Fig 2.1 A CCD image of Albireo (β Cygni) taken from Australia by Steve Crouch, the separation is $34''.7$. N is at the bottom, east to the right

Whilst a telescope enhances the colours in double stars, if too large an aperture is used as James Mullaney (9) pointed out some years ago, colour perception is made more difficult. This can be partly explained by the fact that the smaller telescope produces a larger diffraction disk and the eye is more susceptible to colour in extended images than in point sources.

Colours can be determined in a more systematic manner than by eye estimates which are affected by personal equation. One method is to take colour slides of double stars and project the resulting images against a commercially available colour chart (such as the Macbeth Color Checker) to determine the colour of each component. Such a project was carried out some years ago by a group, led by Joseph Kaznica and others (10) at the Mount Cuba Observatory in Delaware.

2.3 Tests of resolution

2.3.1 Binocular tests

Before the appearance of the stabilising binoculars it used to be thought that the best resolution available with the standard pair of 7 x 50 binoculars was around 25 arc seconds. The limiting magnitude also improves with the field being more stable and again it would be most interesting to see what the limit of these instruments is. Table 1 lists a number of test objects.

2.3.2 Resolution tests for binoculars

The following table gives a list of 50 double stars that are suitable tests for image-stabilised (and other) binoculars. The pairs have been selected from the WDS with the criteria that the magnitudes should both be brighter than 8.0 and the separations lie between 8 and 25 arc seconds. The pairs are well distributed around the sky so a number of them will be visible at any time of year. The positions are given for J2000 and the position angle and separation (in degrees and arc seconds respectively) refers to the date given in the previous column. In most cases the motion is very small but a number of these pairs are binary and are indicated by an asterisk (*) after the catalogue name. The magnitudes are visual and come from the WDS. The components AB refer to the brightest two stars in a multiple system - no components given means that the given pair is a double only. For an explanation of the catalogue names, see Chapter 24.

2.4 Resolution tests for telescopes

The following tables present some test of resolution for telescopes of apertures ranging from 90-mm to 60-cm. These pairs are chosen because they appear to be moving fairly slowly at the present time and the following list should be accurate until about 2005. The pairs are chosen from the CHARA 4th catalogue of interferometric measures (11) and the values given below are for the epoch 2002.0. The complete Catalogue is available on the CD-ROM.

The closest pair in each list corresponds approximately to the Dawes limit for that aperture ($11''$/D in cm) although the magnitude of both components varies so that the fainter and more unequal pairs will be more difficult to resolve than the bright equal pairs of similar separation.

Note that these lists are merely suggestions for testing telescope objectives and test objects should not be selected rigorously from one table. Resolution depends, after all, not only on the collimation and quality of the optics, but the state of the atmosphere. It is most likely that the last word on any attempts to resolve close pairs will be had by the seeing so attempts should be made when atmospheric conditions are suitable.

2.5 References

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Table 2.1 Resolution tests for binoculars

Catalogue	Comp	RA(2000)Dec	Date	PA	Sep	Va	Vb
STF 3053	AB	00026+6606	2007	70	15.0	5.96	7.17
STF 60*	AB	00491+5749	2009	322	13.1	3.52	7.36
STF 100	AB	01137+0735	2009	63	25.5	5.22	6.15
H 2 58		01590-2255	1998	303	8.5	7.28	7.56
STF 205	A-BC	02039+4220	2009	63	9.5	2.31	5.02
STF 239		02174+284	2006	212	13.8	7.09	7.83
PZ 2		02583-4018	2009	91	8.4	3.20	4.12
STF 401		03313+2734	2008	269	11.3	6.58	6.93
STF 550	AB	04320+5355	2009	308	10.3	5.78	6.82
STF 590		04436-0848	2007	318	9.2	6.74	6.78
STF 630	A-BC	05020+0137	2007	53	13.7	6.50	7.71
STF 688		05193-1045	2008	95	10.6	7.52	7.55
STF 872	AB	06156+3609	2007	216	11.4	6.89	7.38
DUN 30	AB-CD	06298-5014	1999	312	11.9	5.97	7.98
HWE 13		06358-1606	1991	296	12.6	7.38	7.51
STF 948	AC	06462+5927	2009	308	8.9	5.44	7.05
STF 1065		07223+5009	2005	255	14.9	7.51	7.67
H N 19		07343-2328	2007	117	9.7	5.82	5.85
STF 1122		07459+6509	2005	186	14.9	7.78	7.80
STF 1245	AB	08358+2009	2009	25	10.0	5.98	7.16
STF1315		09128+6141	2000	27	24.7	7.33	7.65
SHJ 110	AC	10040-1806	2008	274	21.2	6.22	6.97
DUN 97	AB	10432-6110	1998	175	12.4	6.59	7.88
BSO 6		11286-4240	2009	164	13.9	5.13	7.38
DUN 117	AB	12048-6200	2000	149	22.7	7.40	7.83
STF 1627		12182-0357	2008	195	19.9	6.55	6.90
STF 1694		12492+8325	2008	326	21.0	5.29	5.74
STF 1744	AB	13239+5456	2009	153	14.3	2.23	3.88
STF 1821		14135+5147	2009	235	13.3	4.53	6.62
HJ 4690	Aa-B	14373-4608	2002	26	19.6	5.55	7.65
STF 1919		15127+1917	2008	10	23.2	6.71	7.38
LAL 123	AB	15332-2429	2007	301	9.0	7.02	7.00
PZ 4		15569-3358	2007	47	10.6	5.09	5.56
H 3 7	AC	16054-1948	2008	21	14.2	2.59	4.52
DUN 206	AC	16413-4846	2002	265	9.5	5.71	6.76
STF 2202	AB	17446+0235	2009	93	20.7	6.13	6.47
STF 2273	AB	17592+6409	1999	283	21.3	7.31	7.63
SHJ 264	AB-C	18187-1837	2009	52	16.9	6.86	7.63
STF 2417	AB	18562+0412	2009	103	23.0	4.59	4.93
STF 2474	Aa-B	19091+3436	2008	263	16.0	6.78	7.88
STF 2578	AB	19457+3605	2008	125	14.9	6.37	7.04
SHJ 324		20299-1835	2009	237	23.2	5.91	6.68
STF 2727*		20467+1607	2009	266	9.0	4.36	5.03
STF 2769		21105+2227	2009	300	18.0	6.65	7.42
STF 2840	AB	21520+5548	2007	196	17.7	5.64	6.42
STF 2873	AB	21582+8252	2008	67	13.7	7.00	7.47
DUN 246		23072-5041	1999	254	8.8	6.29	7.05

Table 2.2 Tests for 90-mm aperture

Catalogue	Comp	RA(2000)Dec	HIP	PA	Sep	Va	Vb
BU728		23522+4331	17655	10	1.16	8.78	9.06
STF367		03140+0044	5058	134	1.21	8.21	8.26
BU114		13343-0837		167	1.26	8.05	8.18
STF987		06541-0552	33154	176	1.27	7.13	7.29
STF2843	AB	21516+6545	107893	149	1.33	7.07	7.36
STF2583		19487+1148	97473	105	1.43	6.47	6.75
STF1291		08542+3034	43721	312	1.47	6.21	6.43
STF314	AB-C	02529+5304	13424	313	1.55	6.95	7.26
STF1932		15183+2649	74893	263	1.64	7.43	7.48
STF1639	AB	12244+2535	60525	324	1.78	6.79	7.94

Table 2.3 Tests for 15-cm aperture

Catalogue	Comp	RA(2000)Dec	HIP	PA	Sep	Va	Vb
BU341		13038-2035	63738	132	0.61	6.46	6.43
BU316		04528-0517	22692	3	0.80	8.57	8.62
BU232	AB	00504+5038	3926	253	0.88	8.58	8.82
STF13		00163+7653	1296	51	0.95	6.98	7.23
STT403		20143+4206	99749	171	0.93	7.31	7.68
HO475	AB	22327+2625		305	1.06	9.34	9.62
BU694	AB	22030+4439	108845	6	1.00	5.72	7.82

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Table 2.4 Tests for 20-mm aperture

Catalogue	Comp	RA(2000)Dec	HIP	PA	Sep	Va	Vb
A 1504	AB	00287+3718	2252	41	0.54	8.12	8.22
HU517	AB	01037+5026	4971	29	0.56	8.22	8.27
A 347		14369+4813	11467	252	0.57	7.73	7.93
HO44		10121-0613	49961	204	0.58	7.96	8.27
COU482		14213+3050		122	0.60	(9.2	9.3)
HU149		15246+5413	75425	273	0.60	6.68	6.80
BU303		01096+2348	5444	293	0.62	6.65	6.78
HU146		15210+2104	75117	127	0.66	8.82	9.09
BU991		22136+5234		140	0.66	(8.8	8.8)
STT435		21214+0254	105438	235	0.66	7.41	7.46
I 78		11336-4035	56931	98	0.67	5.39	5.44
A 185		22201+4625		319	0.69	(9.6	9.7)
STF412	AB	03345+2428	16664	356	0.70	5.95	5.98
STF2783		21141+5818	104812	355	0.70	7.11	7.34
STF1555	AB	11363+2747	56601	147	0.71	5.80	6.01
STF3056	AB	00046+3416	374	144	0.72	7.02	7.30
A 1116		15116+1008	74348	51	0.77	7.97	7.99
A 2419		03372+0121		96	0.78	(8.6	8.7)
KUI97		20295+5604	101084	132	0.79	5.89	8.77
BU182	AB	23171-1350	114962	47	0.79	8.16	8.38
A 1		01424-0646	7968	248	0.80	8.05	8.20
A 953		01547+5955		65	0.80	(8.8	8.8)
COU610		15329+3121	76127	200	0.82	4.14	6.55
STT112		05398+3758		49	0.84	(7.92	8.2)

Table 2.5 Tests for 30-cm aperture

Catalogue	Comp	RA(2000)Dec	HIP	PA	Sep	Va	Vb
VOU36		02513+0141		9	0.38	(8.4	8.9)
STT75		04186+6029	20105	181	0.38	7.33	7.49
BU688	AB	21426+4103	107137	197	0.38	7.55	7.61
A 1562		05373+4339		352	0.39	(9.0	9.0)
CHR91		20045+4814	98858	211	0.39	6.16	9.64
AC16	AB	19579+2715	98248	232	0.39	7.56	7.77
A 1588		09273-0913	46365	196	0.40	(7.2	7.3)
A 2152	AB	10290+3452	51320	50	0.40	8.52	8.79
RST4534		15089-0610	74116	12	0.41	(8.21	8.2)
RST4220		03038-0542	14255	339	0.42	8.85	8.91
A 2719		06203+0744	30120	65	0.44	6.76	6.83
MCA38	Aa	13100-0532	64238	339	0.44	4.38	6.72
STT349		17530+8354	87534	44	0.45	7.51	7.72
A 951		01512+6021	8629	220	0.45	7.98	8.26
A 914		00366+5608?	2886	26	0.46	7.97	8.05
BU1023		07151+2553	35070	304	0.45	8.34	8.52
A 2016	AB	02287+0840		175	0.46	(9.9	9.9)
YSJ1	Aa	10329-4700	51504	95	0.46	5.02	7.39
BU1184		03483+2223		270	0.46	(8.9	9.1)
BU1298		16595+0942	83143	129	0.46	7.96	8.00
A 1607		13124+5252	64517	14	0.47	9.34	9.43
STT86		04366+1945	21465	4	0.47	7.32	7.34
I 450		01519-2309		222	0.48	(8.6	8.9)
STT337		17505+0715	87325	170	0.48	7.72	7.87
KUI8		02280+0158	11474	38	0.52	6.45	6.66
HU1274		15550-1923	77939	119	0.52	5.95	7.96
COU103		15200+2338		283	0.54	(8.9	8.9)
STT510	AB	23516+4205	117646	304	0.55	7.34	7.41

Table 2.6 Tests for 40-cm aperture

Catalogue	Comp	RA(2000)Dec	HIP	PA	Sep	Va	Vb
COU452		01510+2551	8600	181	0.29	8.08	9.42
HU981		22306+6138	111112	215	0.29	6.98	7.23
COU1214		01373+4015		175	0.31	(9.6	9.6)
COU1659		01298+4547		26	0.32	(9.0	9.3)
STF346		03055+2515	14376	254	0.34	5.45	5.47
BU1147	AB	23026+4245	113788	352	0.35	5.09	7.26
STT250		12244+4306	60522	349	0.35	7.88	8.02
HU520		01178+4946		166	0.36	(8.09	8.3)
A 1204		20143+3129		143	0.36	(9.4	9.7)
COU1510		02016+4107		131	0.36	(9.6	9.6)
COU2037		05219+3934	25060	143	0.37	7.31	7.54
KR12		01415+6240	7895	291	0.37	7.81	7.88
A 1498		23594+5441	118287	90	0.38	7.73	7.77

Table 2.7 Tests for 60-cm aperture

Catalogue	Comp	RA(2000)Dec	HIP	PA	Sep	Va	Vb
COU2013		02520+1831		93	0.21	(9.1	9.1)
A 506		06357+2816		36	0.23	(8.6	8.9)
B 2550	AB	01425+5000	7979	277	0.23	8.41	8.58
COU1505		00594+4057	4626	138	0.23	8.55	8.70
HO 98		19081+2705	93994	78	0.24	7.53	7.54
MCA60	Aa-B	20158+2749	99874	147	0.24	4.50	6.65
COU1183		21180+3049	105146	18	0.25	8.13	8.30

Chapter 3
The Observation of Binocular Double Stars

Mike Ropelewski

3.1 Introduction

The night sky presents a fascinating variety of double stars, ranging from wide, optical pairs to close binary systems. A few doubles can be divided with the unaided eye, while a modest pair of binoculars will reveal many more; the study of double stars can be enjoyed by those who do not possess a large telescope or expensive equipment. There is a broad selection of binoculars on the market, so let us take a look at those that might be suitable for this branch of astronomy.

3.2 Binocular Features

Probably the best views of celestial objects will be obtained using prismatic binoculars (Fig 3.1). In this design, light passes through the objective lenses and is reflected by prisms before being focussed at the eyepieces. Prisms extend the effective focal length of binoculars without increasing their size and create a sharper image than would otherwise be produced. This especially important when observing double stars; the components should appear as individual pinpoints of light. They also invert the image resulting in an upright view.

Image stabilized binoculars include advance design features such as a microprocessor variable-angle prisms. These compensate for involuntary movement, enabling the observer to 'lock on' to a celestial object at the press of a button. The increased steadiness of the image allows a higher magnification to be used without a tripod or dedicated mount. Comparisons with conventional binoculars have been most impressive. (For a list of test double stars see Chapter 2).

Fig 3.1 The light path in a pair or prismatic binoculars

Another feature of good quality binoculars is coated or bloomed lenses, where the optical surfaces are treated with a substance to reduce the amount of light reflected from them. The resulting field of view is brighter and free from haloes and other false images. Bloomed lenses appear blue or purple when studied under white light - a helpful point to remember if the binocular housing has not been stamped with the words ’Coated Optics’.

’Optional extras’ could include eye-cups, which are circular pieces of plastic or rubber fitted around the eyepieces. Eye-cups prevent stray light from entering the eye and are particularly useful when observing from brightly-lit surroundings.

The majority of binoculars achieve focussing by means of a manually rotated centre-wheel located on the axis joining the optical systems. Additionally, it is common for one eyepiece to be individually adjustable ensuring that each image is correctly focussed for the observer’s eyes.

Finally - lens caps. Binocular lenses are delicate items and may incur damage by accidental scratching. A set of tightly fitting covers for eyepieces and objectives will provide valuable protection from mishap and ensure optimum performance is obtained for the lifetime of the binoculars.

3.3 Aperture, magnification and field diameter

Having ensured that our binoculars are of decent optical standard, the next points to consider are aperture and magnification. These factors are important because they will determine whether or not a double star can be resolved into two separate sources of light.

Binoculars such as the popular 7 x 50 range (denoting a magnification of seven times and an objective lens diameter of fifty millimetres) are reasonably priced, lightweight and will provide good views of many double stars plus a host of other interesting celestial objects. They are also suitable for general daytime use. Larger instruments with a higher magnification will divide much closer pairs and show greater detail, but are more expensive and bulky. It may be advisable for beginners to invest in a fairly modest pair of binoculars before progressing to an instrument of greater power and aperture, should a deeper interest in astronomy develop.

The field diameter of a pair of binoculars is a numerical value expressed in degrees and fractions of a degree. It is directly related to magnification and objective lens diameter. For a given aperture, field diameter diminishes as magnification increases. As might be expected, it is easier to locate an object through binoculars with a wide field of view, because the area of sky represented is proportionately larger.

To obtain the field diameter of a pair of binoculars, if this value is not known, we need to note the length of time taken for a star near the celestial equator to drift centrally across the field of view from one edge to another (it is necessary to secure the binoculars to a tripod or some other means of support for the test). Suitable bright stars include δ Orionis (in the belt of Orion), ζ Virginis and α Aquarii. The elapsed time, recorded in minutes and seconds, is multiplied by fifteen to give the field diameter in minutes and seconds of arc. This method can also be used for determining the field diameter of a telescope eyepiece.

3.4 Binocular mounts

Conventional hand-held binoculars will resolve the more widely separated double stars, whilst stabilising binoculars, as described in Section 2, are capable of dividing much closer, fainter pairs. However some form of mounting is essential if field drawing is to be attempted.

Fig 3.2 An example of a simple binocular mount (John Watson)

There are several types of adapter. The example illustrated in Fig. 3.2 consists of a threaded clamp which is tightened around the central axis of the binoculars; the adapter base is secured to the tripod by means of a standard screw thread. An alternative design comprises an L-shaped bracket with a projecting thread at the top end; this style of adapter is suitable for binoculars that have a threaded recess at the objective end of the central axis. Large binoculars may benefit from the extra support provided by the ’heavy duty’ type of clamp which fits around one side of the binocular housing, giving a more stable and rigid observing platform.

3.5 Tripods

It is advisable to choose a tripod that allows binoculars to be secured at slightly above head height, preventing an uncomfortable stoop when studying objects at high altitude. Tripod legs should be strong and sturdy; otherwise, any vibration will be transmitted to the field of view, resulting in a shaky image. Both tripod and adapter can be purchased from any good camera shop. Mounted binoculars are portable, easy to set up on any flat, level surface and will enhance the enjoyment of observing double stars and many other celestial features.

3.6 What can we see?

Table 3.1 provides a selection of double stars divisible in binoculars. Positions and measures have been extracted from the Washington Double Star catalogue (WDS) and observational notes have been added by the author. Many of these double stars are marked in Norton’s Star Atlas (1) which, when supplemented by a publication such as Sky Catalogue 2000.0, Vol 2 (2) , will provide both the binocular and telescope observer with a host of interesting objects.

3.7 Magnitude and separation limits

There are several factors that can affect the magnitude and separation limits (i.e. the faintest stars visible and the minimum separation attainable) for a pair of binoculars.

Table 3.1 Some fine binocular double stars

RA	2000 Dec	Pair	Comp	Date	PA	Sep	Va	Vb	Constell.
0149.6	-1041	ENG 8	AB	2001	251	184.7	4.69	6.81	Cet .
0156.2	+3715	STFA 4	AB	2001	299	200.5	5.79	6.07	And.
0405.3	+2201	STT 559	AB	2003	359	176.8	5.90	8.09	Tau.
0433.4	+4304	SHJ 44	AB	2003	198	120.5	6.12	6.83	Per.
0506.1	+5858	STFA 13	AB	2002	9	178.7	5.20	6.21	Cam.
0530.2	-4705	DUN 21	AD	2000	271	197.8	5.52	6.68	Pic.
0535.4	-0525	STFA 17	AD	1995	316	133.3	5.03	5.06	Ori.
0604.7	-4505	HJ 3834	AC	1999	321	196.2	6.02	6.39	Pup.
0704.1	+2034	SHJ 77	AC	2008	347	101.3	4.05	7.66	Gem.
0709.6	+2544	STTA 83	AC	2002	80	120.5	7.16	7.79	Gem.
0750.9	+3136	STTA 89	AB	2004	83	77.0	6.83	7.69	Gem.
0814.0	-3619	DUN 67	AB	2009	174	65.5	5.03	5.99	Pup.
0855.2	-1814	S 585	AB	2002	151	64.2	5.90	7.24	Hya.
0929.1	-0246	HJ 1167	AB	2009	6	65.6	4.64	7.28	Hya.
0933.6	-4945	DUN 79	AB	1999	33	140.4	7.46	7.62	Vel.
1228.9	+2555	STFA 21	AB	2009	251	144.2	5.23	6.64	Com.
1235.7	-1201	STF 1659	AE	2003	275	153.1	7.94	6.78	Crv.
1252.2	+1704	STFA 23	AB	2010	51	196.5	6.50	6.99	Com.
1313.5	+6717	STFA 25	AB	1999	296	179.0	6.64	7.08	Dra.
1327.1	+6444	STTA 123	AB	2000	147	68.9	6.65	7.03	Dra.
1350.4	+2117	S 656	AB	2003	208	85.9	6.93	7.37	Boo.
1416.1	+5643	STF 1831	AC	2003	220	109.7	7.16	6.73	UMa.
1520.1	+6023	STTA 138	AB	2002	196	152.1	7.64	7.76	Dra.
1536.0	+3948	STT 298	AB-C	2002	328	121.5	6.90	7.75	Boo.
1620.3	-7842	BSO 22	AB	2000	10	103.3	4.90	5.41	Aps.
1636.2	+5255	STFA 30	AC	2009	195	89.0	5.38	5.50	Dra.
1732.2	+5511	STFA 35	AB	2009	312	62.7	4.87	4.90	Dra.
2013.6	+4644	STFA 50	AC	2008	174	106.7	3.93	6.97	Cyg.
			AB	2008	325	333.8	3.93	4.83	Cyg.
2028.2	+8125	STH 7	AC	2000	282	196.6	5.48	6.66	Dra.
2037.5	+3134	STFA 53	AB	2003	177	182.7	6.29	6.54	Cyg.
2110.5	+4742	STTA 215	AC	2009	189	136.3	6.55	7.52	Cyg.
2113.5	+0713	S 781	AB-D	2008	172	183.1	7.25	7.17	Equ.
2143.4	+3817	S 799	AB	2001	61	150.3	5.69	7.00	Cyg.
2144.1	+2845	STF 2822	AD	2001	45	197.5	4.75	6.94	Cyg.

For example, conventional hand-held 7 x 50 binoculars can resolve double stars separated by approximately one minute of arc, whereas image-stabilised binoculars in the 15x45 range can typically reduce this to around 15 arc seconds (3). On the negative side, a bright moon, or artificial lighting can create the all-too familiar sky-glow that renders faint stars invisible, whilst the presence of atmospheric pollution, cloud or haze can also impair observation. This is most obvious when attempting to study objects located at low altitude; incoming light is more readily absorbed by the thicker layer of atmosphere which may, in severe cases, reduce the apparent brightness of a star by several magnitudes.

Table 3.2 Notes on double stars in Table 3

Pair	Notes
ENG8	χ Cet. A white and pale yellow double located SW of the orange 4th mag. star ζ Cet.
STFI4	56 And. Pale yellow, pale blue. Lies on the southern border of the open cluster NGC 752.
STF559	39 Tau. Easy white and bluish-white double. East of the yellow 4th mag. star 37 Tau.
SHJ44	57 Per. Superb, bluish-white pair in a field sparkling with many faint stars.
STFA13	11,12 Cam. Bluish-white, pale yellow. Fine pair. A curved chain of 4 stars following.
DUN21	Orange, blue. Spectacular. Forms a right-angled triangle with two 7th mag. stars.
STFA17	θ^1 - θ^2 Ori. Two silvery-white, 5th mag. twins enveloped by the Orion Nebula.
HJ3834	A neat white pair in a curved E to W chain. The white 4th mag. ? Col. lies NW.
SHJ77	ζ Gem. An unequal, yellow and bluish-white couple on a rich background. Tiny comes.
STTA83	A faint, white double in a dense region near the open cluster NGC 2331.
FRK7	A splendid, white pair, 3 degrees east of β Gem. Preceding a dense field.
DUN67	This bluish-white double forms a parallelogram with 3 other faint stars. Fine area.
S585	A pleasant, pale-yellow pair located south of a W-shaped formation of stars.
HJ1167	τ^1 Hya. White, bluish-white. Unequal. Easily found south of a group resembling Sagitta.
DUN79	An easily resolved pure white couple. The 4th. mag. M Vel. lies N.
STFA21	17 Com. A beautiful, blue pair situated in the Coma Berenices Cluster.
STF1659	This white double lies at the NE end of a chain of 3 tiny stars.
STFA23	32, 33 Com. Pale orange and bluish-white. Lovely contrast. South of the Coma Cluster.
STFA25	A superb orange pair, easily resolved. Situated 3 degrees from STTA123 (see below).
STTA123	Both components are pale yellow. Located in a small arc of fainter stars.
S656	This neat white pair closely follows the yellow 5th mag. star 6 Boo.
STF1831	A splendid, bluish-white double in a field densely populated with tiny stars.
STTA138	This delicate, white pair follows the pale yellow 3rd. mag star ι Dra.
STT298	Both pale yellow. Fine field with 53 Boo (white) and ? Boo (orange) to the NE.
BSO22	A beautiful, golden yellow pair, almost equal in brightness and easy to resolve.
STFA30	Grand, bluish-white pair preceded by a five-star group shaped like a capital X.
STFA35	ν Dra. An exquisite double, comprising two pure white 5th mag. stars.
STFA50	31, o^1 Cyg. Gold, green blue. A magnificent triple star on the fringes of the Milky Way.
STH7	75 Dra. Both stars orange. A fine, bright pair located in a rich area of sky.
STFA53	48 Cyg. Two pure white ’twins’ set in a superb region of the Milky Way.
STTA215	Both stars white. Rich area. The orange, 5th mag. 63 Cyg. lies W.
S781	This equal, bluish-white pair is situated near the centre of the Equuleus quadrilateral.
S799	79 Cyg. Both components white. The SE member of a circlet of six stars.
STF2822	μ Cyg. White and bluish-white. Unequal but easy. Set against a rich stellar background.

These ’minus points’ afflict all visual observers, but should not discourage perusal of the heavens. On a clear, dark night there is much that we can see and do.

3.8 Star Colours

A casual look around the sky will reveal that not all the stars are of the same colour. Antares and Betelgeuse, for instance, are orange-red while Altair and Vega appear bluish or bluish-white. Colour is directly related to a star’s surface temperature and the wavelength of the light emitted. Blue or white stars are hotter than those displaying an orange or red hue. Binoculars show the colours well, particularly where the components of a double star present contrasting shades. Examples include theta Tauri, a prominent yellow and white pair in the Hyades cluster, and the superb gold, blue and green triple o1 Cygni. Conversely, fainter stars on the threshold of visibility appear white because they emit insufficient light to stimulate the colour receptors in the eye.

Occasionally, observers may encounter unusual stellar colours such as violet or mauve. These curious hues are sometimes caused by a phenomenon known as ’dazzle tint’, where a bright primary imparts false colour to its fainter companion. Star colours are naturally subjective, with opinions often varying between experienced observers. This is just one of the intriguing aspects connected with the study of double stars.

3.9 Field drawing

Perhaps the most enjoyable way of permanently recording a double star observation is to make a field drawing, together with a short written description of the object under study. Sketching trains the eye to notice fine detail and the results can be both personally rewarding and scientifically useful.

Before starting to sketch, it is necessary to prepare some blank circles to represent the field of view. These may be drawn using a pen and template or on a computer/word processor. A field diameter of six centimetres enables six circles to fit on a sheet of A4 paper, allowing sufficient space for captions and notes. For those observers who do not own a printer, it may be convenient to produce a page of blank circles which can be photocopied as required.

Other items needed for field drawing are a medium grade black pencil, eraser, sketch-board and a red torch. Especially useful is the ’clip-on’ design of torch, which can be attached to the drawing board, allowing the observer to sketch more easily.

Fig 3.3 An example of a field drawing

The next three steps involve finding a light-free observational position, securing the binoculars to a mounting and choosing a suitable double star. Celestial objects near the meridian (due south in the northern hemisphere and due north in the southern hemisphere) are easy to follow because their altitude does not vary much as they cross that part of the sky. After locating the double and before sketching, it may be worth panning the binoculars slightly in altitude and azimuth to obtain the most interesting field of view.

One method of creating a sketch is to begin by drawing the components of the double and the brightest field stars that are visible. Fainter ones can then be added, using the principal stars as reference points. The larger the pencil dot, the brighter the star it represents.

An alternative technique involves dividing the field of view into four equal segments or quadrants and drawing all the stars visible in each section. This approach is, however, probably better suited to telescopic observation, where the field can be accurately divided using an eyepiece fitted with cross hairs.

The pencil sketch can be overwritten with black ink, if desired, and supplemented by a brief caption. A concise field description could also be included, either with the diagram or, if preferred, in a separate notebook or on a database. An example of a completed field drawing is shown in Fig 3.This diagram has been reproduced from the publication 'A Visual Atlas of Double Stars' (4) which contains observational details of more than three hundred double stars suitable for both binoculars and telescopes.

3.10 Summary

The observation of binocular double stars is an absorbing pastime and provides a good introduction to some of the 'showpieces' of the night sky. It may lead to more detailed telescopic study of these underrated celestial objects or be enjoyed as a hobby in its own right. Either way, it is a most fascinating branch of astronomy.

3.11 References

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Chapter 4
The scale of binary systems

Bob Argyle

4.1 Introduction

How much we can find out about binary systems depends mostly on the separation of the two stars. Very wide pairs with rotation periods of many thousands of years yield little direct information whilst close pairs with short periods and an orbital plane in the line of sight, thus producing eclipses, will allow many of the individual physical characteristics of the stars such as mass, size and brightness to be measured.

The most common type is the visual binary but this is simply due to the fact that these systems are near enough to us that we can resolve them optically. It is quite likely that during the next 10 or 20 years as more sophisticated satellites such as GAIA are launched the number of binary stars known is likely to increase tremendously. This is to be expected since near the Sun we know that more than half our stellar neighbours are members of binary or multiple systems and there is no reason to suppose that this is just a phenomenon peculiar to this region of the Galaxy. At the time of writing the WDS catalogue contains more than 99,000 systems.

4.2 Periods greater than 1,000 years

There is a huge range of scale in binary star orbits and consequently the period can, at the longer end, reach 100,000 years or more. The upper limit is set when the separation of the two stars becomes comparable to the distance to other nearby stars. In this case, the external influences of the neighbourhood stars will eventually disrupt the very tenuous gravitational link between the components of the binary. Periodic passages through the plane of our galaxy (which happens every 30 million years or so) can also disrupt wide binaries due to the influence of giant molecular clouds. It is, of course, impossible to determine these periods even remotely well and even orbital determinations with periods of 1,000 years are regarded as very provisional. For the widest systems, the separation of the two stars can reach 10,000

Astronomical Units (by comparison Pluto is about 30 AU from the Sun and the distance to α Centauri is 280,000 AU).

4.3 Periods between 100 and 1,000 years

Between periods of 100 and 1,000 years lie many of the binaries that can be seen with small telescopes such as Castor (445 years), γ Leo (510 years) and γ Vir. (169 years). The Sixth Catalogue of Orbits of Visual Binary Stars, from the United States Naval Observatory (on the CD-ROM) attempts to list and assess the various orbits which have been calculated for visual binaries. Each orbit is graded from 1 (definitive) to 5 (preliminary) and there are no definitive orbits for binaries with periods greater than that of 70 Oph. (88.38 years). (The Sixth Catalogue is the regularly updated version available on-line at the USNO website). This is due to the fact that it is only from around 1830, when F.G.W.Struve was well into his stride at Dorpat working with the 9.6-inch refractor that reliable (and numerous) measures exist. Clearly it is still important to work on these systems, even though the results may not be used for several centuries. It was the great Danish astronomer Ejnar Hertzsprung who said “If we look back a century or more and ask ‘What do we appreciate mostly of the observations made then?? The general answer will be observations bound to time. They can, if missed, never be recovered. Of these observations, measures of double star contribute a major part”.

4.4 Periods between 10 and 100 years

For the serious amateur, pairs with periods between 10 and 100 years are the most rewarding in terms of being able to follow them over a significant portion of their apparent orbit. A good example of a pair in this category is ζ Her. with a period of 34.385 years. The apparent separation ranges from 0.5 to 1.5 arc seconds, but because the pair is unequally bright (2.8 magnitudes in V) when it is near periastron to see it requires at least a 30-cm aperture. It should be noted that many of these pairs are grade 1 although it is almost certain that Hipparcos will have added pairs in this region of which very few observations have ever been made from the ground and which would benefit from further coverage. These are likely to be difficult visually, however. All of the Hipparcos discoveries can be found in the WDS catalogue on the CD-ROM.The discovery code is HDS whilst TDS and TDT indicate additional pairs found by the satellite from the Tycho project.

4.5 Periods between 1 and 10 years

Between 1 and 10 years period, measures of pairs need large apertures and sometimes special techniques - such as speckle interferometry. Pairs in this region are almost all beyond the range of small apertures.

4.6 Periods less than 1 year

To detect stars as binary in this period regime, which is beyond the scope of this book, it is necessary to turn to the spectrograph or the ground-based optical array. For an excellent description of the many and varied types of close binary systems see the book by Hilditch (1).

4.7 References

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Chapter 5
Multiple stars and planets

5.1 Binary star formation

Observational evidence strongly suggests that double stars are the rule rather than the exception in our galaxy. Recent studies of molecular clouds, using sensitive infra-red and millimetre wave detectors (because the visual absorption can exceed 1000 magnitudes), have shown that many of the objects found in there are double or multiple.

Stars are born in dense clouds which consist almost totally of molecular hydrogen along with a small admixture of dust. At the temperature typical of these clouds, about 10K, the hydrogen cannot be detected. Most clouds also contain traces of carbon monoxide which produces very bright spectral lines at wavelengths of 1.3 and 2.6 mm and it is these which allow astronomers to trace the distribution of hydrogen. To date about 120 other molecules have been found ranging from water and ammonia to more complex organic structures such as methanol and ethanol.

Molecular clouds come in a range of sizes and composition. The small cloud complex Chamaeleon III for instance is about 10pc in diameter, has a maximum visual extinction of a few magnitudes and temperature of about 10K. There are a few stars, none of which are massive and no star clusters. The largest complexes in Orion, however, are perhaps 50 pc across, with 100 magnitudes of visual extinction and a gas temperature of 20K. These are populated by thousands of stars in dense clusters, including massive OB stars. Star formation occurs most frequently in the more massive clouds. Other well-known regions of star formation are known simply by the constellation in which they appear - Taurus-Auriga, Ophiuchus, Lupus, and Perseus for example.

How then do binary stars form from the nascent interstellar material? Recent simulations on powerful computers can explain not only many of the observed properties of binary stars but also the existence of large numbers of brown dwarfs. These are objects which, in terms of their mass, lie between the massive Jupiter-like planets and the faintest of stars - the red dwarfs. The mass of brown dwarfs (about 0.07 times that of the sun or alternatively 70 Jupiter masses) is not sufficient for the nuclear reactions in the core to start but they are warm enough to be seen in sensitive infra-red detectors.

Bate et. al. (1) have recently published the results of collapsing a simulated interstellar cloud in the computer and following its evolution. They begin with a cloud of 50 solar masses and about a light year in diameter and the process starts with the formation of cores which then collapse gravitationally, some being more massive than others. The dense cores are usually surrounded by a dusty disk which is left behind as they contract more and more rapidly. These disks are thought to be the major source for the formation of brown dwarfs. Many interactions occur within the cloud before the stars have reached their full size and as a result the less massive fragments are ejected from the cluster by a slingshot mechanism. The most massive cores are attracted to each other and form close binaries and multiple systems which then undergo further evolution.

When the calculation was stopped (it took 100,000 CPU hours!) the result was formation of 23 stars and 18 brown dwarfs so Bate and colleagues conclude brown dwarfs should be as common as stars. The number of known brown dwarfs is very small but that is largely due to the fact that they are so difficult to detect. Another prediction of this programme is that brown dwarf binaries do form but they need to be very close in order to survive and the few binary brown dwarfs found so far fit this criterion. It was previously thought that the production of close and wide binaries was a result of different processes but this current theory has the advantage to producing many of the observed properties of multiple stars and brown dwarfs.

5.2 Planets in binary systems

When the first edition of this book appeared in 2004 there were around 15 known cases of planets or planetary systems orbiting one component of a binary star. At the time of writing this number has risen to 60 or so, most of which are listed in Table 1. There are two common ways in which planetary bodies (exoplanets) can exist in binary star systems in a dynamically stable configuration (see Fig 5.1)

Firstly the planet orbits well outside a pair of stars in a close binary orbit. This is referred to as a P-type (or planetary type) orbit. In this case there exists a critical value of the semi-major axis of the planet's orbit around the pair. Too close and the planet is subject to competing pulls from both stars -too distant the gravitational link vanishes.

Secondly the planet orbits one or other of a wide pair of stars where the distance of the planet from its sun is much less that the stellar separation. This is an S-type (or satellite-type) orbit and here the semi-major axis of the planetary orbit must be less that a certain critical value if the perturbations from the second star are not to be too disruptive. In other words if the planet wanders too far from its sun during its orbital revolution it will come under the influence of the companion star. To date, all known exoplanets have S-type orbits, but with the discovery of exoplanets in close binary systems then it would be reasonable to expect P-type orbits to be found. So far, there are no cases in which each component of a stellar binary is attended by planets or a planetary family.

A third possibility is the L-type orbit in which the planet moves in the same orbit as the secondary but but 60 degrees ahead or behind it.

Fig 5.1 Location of stable planetary orbits (a) the S-type (Satellite-type) and (b) the P-type (Planet-type)

At the time of writing (June 2011) some 550 exoplanets are known. In some 80% of cases these objects have been discovered by the reflected variation in radial velocity of the primary star but other methods have also been used. Astrometry of host stars using HST for instance can reveal planetary perturbations; in those rarer cases where the plane of the planetary orbit lies in the line of sight, the planets betray their presence by transiting the primary star, and more recently deep imaging in the infra-red has revealed planetary bodies directly. All the planetary orbits known to date are S-type and are listed in the table below. The Msin i column lists the minimum mass (in Jupiter masses) that the planet has, and the sini term represents the unknown inclination of the planetary orbit. There are now about 100 cases known in which the exoplanet or exoplanets transit the parent sun giving sin i = 90 degrees so the true planetary mass equals the minimum mass.

The first discovery was a planetary companion to one of the stars in the wide pair 16 Cyg. The planet was detected orbiting the fainter of the two stars which separated by some 39 arc seconds on the sky, equivalent to a linear separation of 700 astronomical units at the distance of 70 light years. The orbital period is very long and nothing is known about orbit of the two stars about the center of gravity. 16 Cyg B is a dwarf star, somewhat earlier in spectral type than the Sun. The planet orbits star B at a distance of about 1.72 AU with a period of 800 days but the orbit is very eccentric (0.63). The recent discovery of a very faint star close to A which is probably physical means this is the first triple star known to have a planetary companion.

55 Cnc is accompanied by a distant M dwarf star which was first identified by W.J.Luyten. The stars make up the system LDS6219. Currently the separation is about 83 arc seconds and has shown little change since 1960. The primary star has an annual proper motion of about 0.5 arc seconds so it is clearly a physical pair but the orbital period is going to be of the order of thousands of years. Two further planets were confirmed in summer 2002, one of which has the smallest value of MJ sin i yet found (0.22).

τ Boo has a faint (mag 11.1) M2 companion which was discovered by Otto Struve at Pulkova. At that time (1831) the separation of 15 arc secs was such that the pair could be relatively easily seen. The distance has closed significantly and the current value is around 3 arc seconds. An orbit was computed in 1998 by A. Hale and a period of 2000 years derived. This is very uncertain but the determination of the binary star orbital elements is significant because from these observations the inclination of the orbit can be determined. If we assume that the planetary orbit around τ Boo is co-planar with that of the two stars then a direct measure of the planet's inclination will allow the mass of the planet to be determined directly. If the binary orbit inclination is correct and the tilt of the planetary orbit to the line of sight is also 50 degrees then the sini factor is 0.77, giving a value of 3.0 Mj for the planet in this system.

The brightest component of the pair STF1341, HD80606 is now known to have a planetary companion with a period of 111.8 days. The eccentricity of the orbit (0.927) is the highest yet found and it is possible that this is due, like that of the planet of 16 Cyg B, to perturbations by the second star in the system.

The wide pair STF2474 consists of two 8th magnitude stars separated by 16 arc seconds. McAlister found the primary to be a close pair with a period of 3.55 years and recently Zucker et al found a planetary mass companion to star B which is a G8 dwarf star of 0.87 solar mass.

The bright star gamma Cephei is a spectroscopic binary of very long period - in fact the longest yet found. Roger Griffin (2) gives the period as 66 years with an uncertainty of 1 year. The planet has a period of 903 days and its average distance from star A is 2.1 AU.

The first planetary discovery made by Italian astronomers with the 3.5-metre Telescopio Nazionale Galileo on La Palma is a low-mass planet orbiting the fainter component of the pair STF 2995 - currently separated by 5.2 arc seconds. The large proper motion of the bright component and the small change in separation since 1820 confirm that the stellar pair is a binary one.

The following table summarises the data that we have at present for the binary systems which have planets. The first column gives the popular name of the binary component with the planet, followed by the double star catalogue name, the approximate separation of the two stars (in Astronomical Units), a letter representing the planet (b = nearest the star, c is next most distant and so on), and finally the minimum mass of the planet (in terms of the mass of Jupiter). If it was possible to observe the planet by direct imaging, we could determine the inclination of the planet's orbit and hence it's mass. If the orbital plane of the planet is in the line of sight then sin i =1 and the mass of the planet can be determined exactly. This is the case in only one out of the 100 or so planetary systems found to date.

A recent paper by Lowrance et al.(3) lists 11 binary and triple systems which have a planetary companion or planetary system in orbit around one of the stars. Recent discoveries include two more planets in the 55 Cnc system, a new stellar component to ? And which already has 3 planets, a faint stellar companion to HD 114762 and a sub-Saturnian mass planet to HD 3651 whose faint stellar companion is field star.

The website maintained by Jean Schneider (4) at Paris Observatory is kept up-to-date with new planet discoveries.

Planet discovery is proceeding apace and many further examples are bound to be found in the near future when the upcoming space interferometer missions such as SIM and DARWIN which are designed to seek out Earth-sized planets start operation. We will soon know whether such planets exist in double or even multiple star systems.

Table 5.1 Planets in known double star systems (January 2011)

Star	RA (2000)	Dec (2000)	Cat.	Mags	PA (°)	Sep (″)	S. type	Nplan	Dist. (pc)
GJ 4.2	00 06 19	-49 04 30	HDO 180	5.7 11.5	184	4.1	G1IV+	1	20.6
GJ 3021	00 16 12	-79 51 04		4.9 14.9	106	2.6	GXV+ M4V	1	17.62
GJ 27	00 39 21	+21 15 01	$O\Sigma$550	6.0 11.5	80	167.6	K0V	linear?	
ν And	01 36 48	+41 24 38	LWR 1	4.2 9.4	149	55.6	F8V+	3	13.47
GJ 81.1	01 57 09	-10 14 32	GAL 315	6.5,12.0	134	29.6	G5IV	2	33.98
GL 86	02 10 14	-50 50 00	ESG 1?	4.8,14.2	103	2.0		1	11
HD 16141	02 35 19	-03 33 38	MUG 2	6.9,	187	6.2	Another at 23"	1	35.9
HD 19994	03 12 46	-01 11 45	HJ 663	5.1,11.0	213	2.5	F8V+	1	22.38
HD 20782	03 20 03	-28 51 14	LDS 93	7.4,8.4	358	253.0	G3V+	1	36.02
HD 38529	05 46 34	+01 10 05	RAG 1	6.0,	305	284.0	G4V+M3V	3	42.43
HD 41004	05 59 50	-48 14 23	HDS 814	8.8,12.5	167	0.4	K2V+		43.03
HD 46375	06 33 13	+05 27 46	SLE 299	9.1,11.0	310	10.3	K1IV+	1	33.4
HD 40979	06 04 30	+44 15 38	LEP 22	6.7,9.1	289	192.5		1	33.3
HD 58728	07 27 44	+21 26 43	MCA 30	5.3, 7.3	349	0.1	F5V+F5V		
HD 60318	07 38 09	+30 57 39	$O\Sigma$175	6.1,6.5	148	0.1	KOIII+		
HD 65216[a]	07 53 41	-63 38 50	MUG 8	6.4,12.7	89	6.4		1	34.3
55 Cnc	08 52 37	+28 20 02	LDS 6219	6.0,13.0	128	84.7	G8V+	1	58.38
HD 80606	09 22 37	+50 36 13	Σ1341	9.1,9.2	89	20.7	G5+G5	5	13.02
γ^1 Leo	10 19 58	+19 50 29	Σ1424	3.4,3.6	125	4.6	KOIII+G5III	1	38.5
HD 89744	10 22 10	+41 13 46	WIL 2	5.9,14.9	51	63.0		1	40
HD 99492	11 26 45	+03 00 47	STF1540	6.6,7.5	146	29.1	G7V+	1	17.67
HD 101930	11 43 30	-58 00 24	MUG 9	8.3,10.7	8	73.1		1	30.49
HW Vir									
HD 109749	12 37 16	-40 48 43	R 203	8.3,10.5	180	8.3	G3V+	1	59
HD 114762	13 12 19	+17 31 01	PAT 47	7.4,18.	30	3.3		1	39.46
HD 114729	13 12 44	-31 52 24	MUG 3	6.8,	333	8.1		1	35
τ Boo	13 47 17	+17 27 22	STT 270	4.5,11.1	33	2.8	F6IV+M2	1	15
HD 125612	14 20 54	-17 28 53			163	90.0	G3V+M4V	3	52.8
HD 126614	14 26 48	-05 10 40	LDS4465	9.7,17.0	299	41.9	K0+		
HD 142022	16 10 15	-84 13 33	HJ 4798	7.7,11.2	130	20.4	K0+	1	35.87
HD 147513	16 24 01	-39 11 34	RAG 8	5.4,11.0	248	350.0	G1V+DA2	1	12.9
HD 156846	17 20 34	-19 20 01	A 2241	6.6,14.1	76	5.2	F9V	1	49
HD 176051	18 57 02	+32 54 05	β648	7.3 8.0	268	0.9	G0V+		
HD 177830	19 05 20	+25 55 14	EGN 24	7.2,	85	1.6	K0+M3.5V		
HD 178911[b]	19 09 03	+34 36 00	STF 2474	6.8,7.9	263	16.0	G1V+		
16 Cyg B	19 41 51	+50 31 03	STFA 46	6.0,6.2	133	39.9	G1.5V+	1	21.41
HD 188015	19 52 04	+28 06 01	RAG 3	8.2	85	13.0	G5IV+	1	52.63
HD 188753	19 54 58	+41 52 18	HO 581	8.0,8.7	133	0.3			
HD 189733	20 00 43	+22 42 39						1	19.3
GJ 777	20 03 37	+29 53 49	LDS 6339	5.7,14.8	232	178.2	G6IV	2	15.89
HD 195019	20 28 17	+18 46 12	HO 131	7.0,10.6	330	3.5	F1V+	1	37.36
HD 196050	20 37 51	-60 38 04						1	46.9
HD 196885	20 39 51	+11 14 58	CVN 17	5.5,9.1	66	0.7	F8IV:+ M1V	1	33
HD 212301	22 27 30	-77 43 04	HDO 299??	6.8,12.0	275	4.4	F8V + M3V	1	52.7
HD 213240	22 31 00	-49 25 59							
HAT-P-1	22 57 47	+38 40 30	HJ 1832	9.8,10.2	74	11.2	F8+	1	13.9
HD 219449[c]	23 15 53	-09 05 15	STFA 12	4.4,9.9	313	50.3	K1III+K3	1	45
HD 219542	23 16 34	-01 35 03	HDO 317		191	9.2			
γ Cep	23 29 20	+77 37 56		3.2,	257	0.9	+M4V	1	13.79
HD 221673	23 33 57	+31 19 31	β720	5.7, 6.1	100	0.5	K4IIIb+		
HD 222582	23 41 51	-05 59 08	LDS 5112	7.7,14.5	300	109.4	G5+		

[a] HD 65216 B is a close double [b] HD 178911 A is close binary CHR 84 P = xx years [c] HD 219449 B is a close binary β1220

5.3 References

(1) Bate, M. (see http://www.ukaff.ac.uk/pressreleases/release3.shtml)

(2) Griffin, R.F., 2002, Observatory, 122, 102

(3) Lowrance, P. J., Kirkpatrick, J., D. and Beichman, C. A., 2002, Ap.J., 572, L79.

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Chapter 6
Is the Sun a double star?

As we have seen the Sun is, as a single star, apparently in a minority amongst the stars in the local neighbourhood. As more very faint companions to nearby stars are found this will make it even more unusual, but do we really live in a solar system with a single Sun?

In 1984 Raup and Sepkowski (1) reported evidence for a 26 million year (Myr) periodicity in the occurrence of mass extinctions based on a study of marine fossils. Such impacts included the one 65 million years ago that produced the Chicxulub crater in Yucatan and killed the dinosaurs. Steel (2) refers to later work by Sepkowski which indicates ten such events over the last 260 million years which strongly correlate with a 26 Myr cycle.

This produced a flurry of interest from astronomers who came up with several ideas on how this could be linked to astronomical events. One idea related to the rotation of the Solar System around the galaxy. It is well established that one rotation around the galactic centre takes about 250 Myr but during this time the Sun also moves perpendicular to the galactic plane in a sinusoidal fashion and crosses the plane every 30 MYr or so, reaching a distance of about 100 pc from the plane at the ends of the cycle. During the plane passage, it is surmised, the Earth's biosphere can be exposed to increased levels of radiation. (A recent theory speculates that another intense source of radiation may emanate from supernovae which tend to occur in the galactic plane). Rampino and Stothers in Nature (3) argued that the original Rapp and Sepkowski data could be interpreted as having a period of 30 Myr rather than 26 then stated that this is in better agreement with the periodic galactic-plane crossing period of 33 MYr. With the Sun spending more than two-thirds of its time within 60 pc of the galactic plane there was ample opportunity for encounters with passing giant molecular clouds to disturb comets from the Oort cloud. Rampino and Stothers also found a periodic term of 31 Myr in the occurrence of large craters on the Earth.

In the same edition of Nature the American astronomers Whitmire and Jackson (4), and, independently, Davis, Hut and Muller (5) came up with a theory to try and explain the apparent 26 Myr periodicity. Whitmire and Jackson postulated a star with mass between 0.0002 and 0.07 M sun with an orbit of eccentricity 0.9 and semi-major axis of 88,000 AU. The companion postulated by Davis et al. was similar but at apastron such an orbit would take it out to a distance of about 3 light years after which the companion would then approach the Sun, skirt the Oort cloud, disrupting comets into the inner solar system and return again to the depths of space. This companion star was named Nemesis to reflect the catastrophes that its appearances would trigger. Detractors from the theory argued that when at apastron passing stars would have more effect on Nemesis than the Sun but work by the Dutch astronomer Piet Hut argued that Nemesis could survive such encounters for about a billion years. Today it is difficult to explain binary orbits on this scale. None out of the 1,000 or so binary orbits which have been catalogued have aphelion distances on this scale.

The main argument against the Nemesis theory is that the projected orbit is too large and too eccentric to allow the star to stay bound to the Sun after more than a few passages through the Galactic plane

Recent studies of wide binaries (6) conclude that some wide pairs have separations in excess of 10,000 AU. To give an idea of this scale, Pluto is about 30 AU away and Centauri is about 280,000 AU distant.

If Nemesis exists then clearly it is not a twin of the Sun because even at apastron it would be apparent magnitude +3 and its parallax of well over 1 arc second would have marked it out many years ago. Nemesis must be at least a faint red dwarf, perhaps even a brown dwarf whose apparent magnitude is likely to be at least +15. The proper motion of such a star will be very small and this will be a distinguishing feature as many very faint nearby stars have large proper motions. So a survey such as the Sloan Digital Survey could pick it up, providing the star lies in the 25% of the sky which the survey will cover. Any suitable candidates could then be observed individually by ground-based telescopes since the parallax will be large.

Could the extinction in the late Eocene period be due to a passing star? One possibility of resolving this question may come with data from the projected GAIA mission. The expected accuracy of the proper motion and parallax determination for the stars in the solar neighbourhood will allow a more accurate backward interpolation to determine the history of close stellar approaches to the Solar System.

6.1 References

(1) Raup, D.M. & Sepkowski, J.J., 1984, Proc. Natu. Acad. Sci. USA, 81, 801.

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Chapter 7
The orbital elements of a Visual Binary Star

Andreas Alzner

7.1 The true orbit

Whilst astronomers regard the brighter component as fixed and map the motion of the fainter one around it , in reality, both stars in a binary system move in ellipses around the common centre of gravity. The size of the ellipse is directly proportional to the mass of the star, so in the Sirius system, for instance, the primary has a mass of 1.5 sun, the white dwarf companion 1.0 sun and so the size of ellipses traced out on the sky are in the ratio 1.0 to 1.5 for the primary and secondary (Fig 7.1). The ratio of the masses is inversely proportional to the size of the apparent orbits (see eqn 1.1) so this gives one relation between the two masses. To get the sum of the masses requires the determination of the true orbit from the apparent orbit and this is what this chapter will describe.

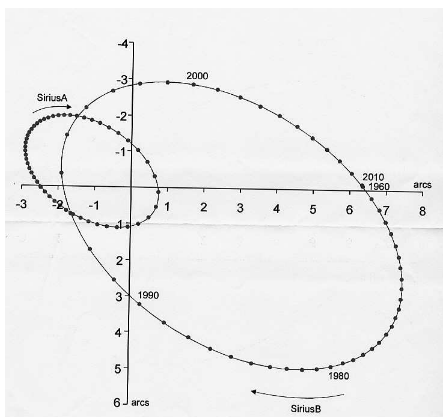

Fig. 7.1 The real orbits of the stars in the Sirius system

We regard the primary star as fixed and measure the motion of the secondary star with respect to it and in Chapter 1 we saw that in binary stars the motion of the secondary star with respect to the primary is an ellipse. This is called the apparent ellipse or orbit and is the projection of the true orbit on the plane of the sky. Since the eccentricity of true orbits can vary from circular to extremely elliptical (in practice the highest eccentricity so far observed is 0.975), then the range of apparent ellipses is even more varied because the true orbit can be tilted in two dimensions at any angle to the line of sight. We need the true orbit in order to determine the sum of the masses of the two stars in the binary. This is still the only direct means of finding stellar masses.

On the face of it then the measurements that we make of separation and position angle at a range of epochs are all the information that we have to try and disentangle the true orbit from the apparent orbit. We do, however also know the time at which each observation was made much more precisely than either of the measured quantities. There are other clues, for instance in the way that the companion moves in the apparent orbit.

In Fig 7.2 I plot the apparent motion of the binary O? 363. In this case x,y rectangular coordinates are used rather than the ? polar coordinates which are more familiar to the observer. Each dot on the apparent ellipse represents the position of the companion at 2 year intervals. It is immediately clear that the motion is not uniform but it considerably faster in the third quadrant i.e. between south and east. The point at which the motion is fastest represents the periastron (or closest approach) in BOTH the true and the apparent orbits.

Keplers Second Law which tells us that areas swept out in given times must be equal and this also applies to both the true and the apparent orbit. In Fig 7.2 although the three shaded areas are shown at different points in the apparent orbit because they are all traced out over a 10 year interval the areas are the same. We also know that the centre of the apparent orbit is the projected centre of the true orbit. In most cases the motion is described by the fainter star relative to the brighter star that is fixed in the focus of the ellipse as if the total mass were concentrated in the fixed centre of attraction.

According to the law of gravitation the primary star and the companion move around the centre of gravity, the first describing the smaller ellipse. In most cases the motion is described by the fainter star relative to the brighter star that is fixed in the focus of the ellipse as if the total mass were concentrated in the fixed centre of attraction.

In the true orbit the centre of the ellipse is called C, the focus, where the brighter star is located is called A. The periastron P is the closest point of the ellipse to A. The geometry of the motion suggests use of polar coordinates. The elements of the real orbit are as follows (Figure 7.3):

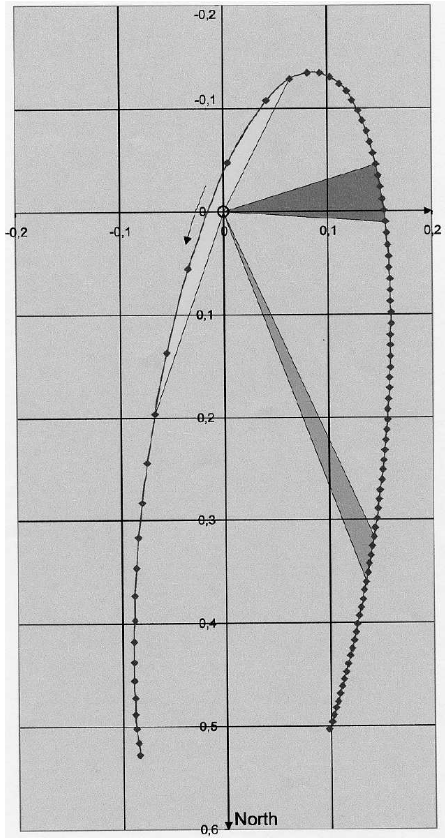

Fig. 7.2 The apparent orbit of a visual binary star

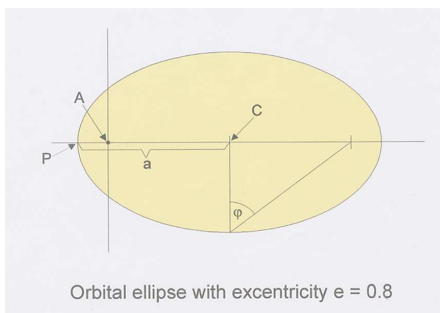

Fig. 7.3 The true elements of a visual binary star

P the revolution period in years; alternatively the mean motion per year ($n = 360/P$ or $\mu = 2\pi/P$ is given,)
T the time passage through periastron,
e the numerical excentricity e of the orbit, the auxiliary angle ϕ is given by $e = sin\ \phi$
a the semiaxis major in arc sec.

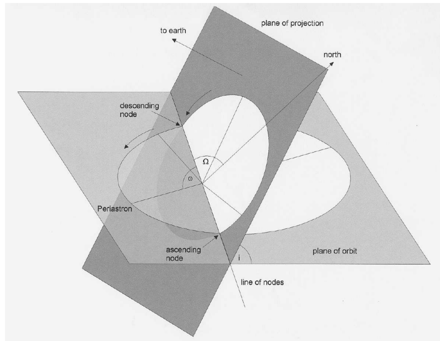

Fig. 7.4 The true and the projected elements of a visual binary star

7.2 The apparent orbit.

The apparent (observed) orbit results from a projection of the true orbit onto the celestial sphere. Three more elements determine this projection:

Ω the position angle of the ascending node. This is the position angle of the line of intersection between the plane of projection and the true orbit plane. The angle is counted from North to the line of nodes. The ascending node is the node where the motion of the companion is directed away from the sun. It differs from the second node by 180° and can be determined only by radial velocity measurements. If the ascending node is unknown, the value $< 180°$ is given.

i the orbital inclination. This is the angle between the plane of projection and the true orbit plane. Values range from 0° to 180° . For $0° \leq i < 90°$ the motion is called direct. The companion then moves in the direction of increasing position angles (counterclockwise). For $90° < i \leq 180°$ the motion is called retrograde.

ω the arguyent of periastron. This is the angle between the node and the periastron, measured in the plane of the true orbit and in the direction of the motion of the companion.

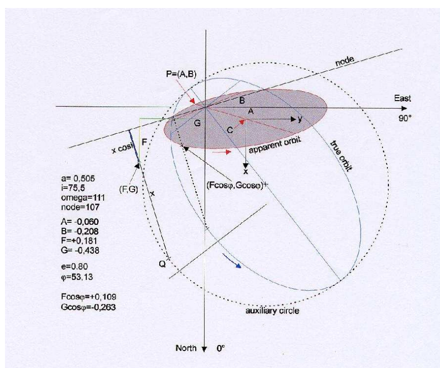

Fig. 7.5 The projected elements of a visual binary star

The elements $P, T, a, e, i, \omega, \Omega$ are called the Campbell elements. There is another group of elements which is used in order to calculate rectangular coordinates. They are called Thiele-Innes elements:

$$A = a(cos\ \omega cos\ \Omega - sin\ \omega sin\ \Omega cosi)$$

$$B = a(cos\ \omega sin\ \Omega + sin\ \omega cos\ \Omega cosi)$$

$$F = a(-sin\ \omega cos\ \Omega - cos\ \omega sin\ \Omega cosi)$$

$$G = a(-sin\ \omega sin\ \Omega + cos\ \omega cos\ \Omega cosi)$$

Note: the elements A, B, F, and G are independent of the excentricity e The points (A, B) and $(F cos\phi, G cos\phi)$, together with the centre of the apparent ellipse, define a pair of conjugate axes which are the projections of the major and minor axes of the true orbit.

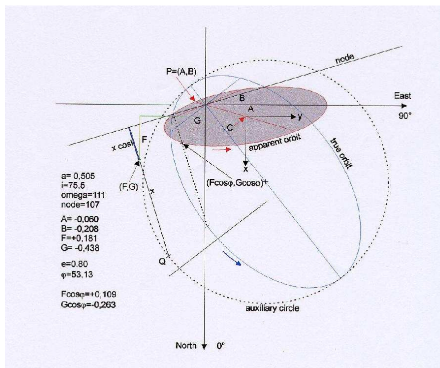

Fig. 7.6 Thiele-Innes elements and Campbell elements

There is an instructive and easy way to draw the apparent orbit from the 7 Campbell elements. It runs as follows:

- Draw the rectangular coordinate system with a convenient scale. North is at bottom (the positive x - axis), East is at right (the positive y - axis).
- Draw the line of nodes: the node makes the angle Ω between north and the line of nodes.
- Lay off the angle ω from the line of nodes and proceeding in the direction of the companion's motion, i.e. clockwise, when $i > 90°$, and counterclockwise, when $i < 90°$. This will give the line of periastron and apastron of the true orbit.
- Draw the true orbit ellipse. The distance of the centre of the true orbit from the centre of the coordinate system is c. The long axis is $2a$, the short axis is $2b$ so b and c are easily calculated:

$$c = ae; \quad b = \sqrt{a^2 - c^2}$$

- Construct the apparent orbit: Draw lines from points on the true orbit to the line of nodes; the lines have to be perpendicular to the line of nodes. Multiply the lines by *cos i*. Connecting the so obtained points yields the apparent orbit.

As an example the orbit for $O\Sigma235$ is given. Elements are as follows (Heintz, 1990): P = 73.03 years, T = 1981.69, $a = 0''.813$, e = 0.397, $i = 47^\circ.3$, $\omega = 130^\circ.9$, $\Omega = 80^\circ.9$.

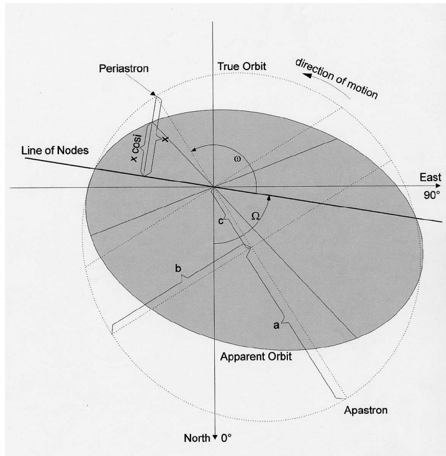

Fig. 7.7 The true and the projected orbit of $O\Sigma235$ drawn in one plane. Note: the law of areas holds in the projected ellipse as well.

7.3 Ephemeris Formulae

For any time t, the coordinates Θ, r or x, y are computed from the elements by means of the following formulae. First the eccentric anomaly E has to be determined from the mean anomaly M:

$$\mu(t-T) = M = E - e \sin E \quad \text{(Kepler's Equation)}$$

This equation is transcendental and has to be solved iteratively. A first approximation is given by the formula:

$$E_0 = M + e \sin M + (e^2/2) \sin 2M$$

This E_0 is used to calculate a new M_0:

$$M_0 = E_0 - e \sin E$$

A new E_1 is obtained from M, M_0 and E_0:

$$E_1 = E_0 + \frac{(M - M_0)}{(1 - ecosE_0)}$$

The last two formulae are iterated to the desired accuracy. Four iterations are sufficient for $e \leq 0.95$. Now the desired positions are calculated:

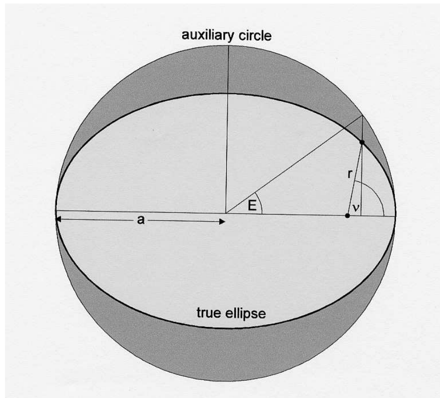

Fig. 7.8 Auxilairy circle, eccentric anomaly E, true anomaly v and radius vector *r)*

Polar coordinates:

$$tan\frac{\nu}{2} = \sqrt{\frac{(1+e)}{(1-e)}}tan(E/2)$$

$$r = \frac{a(1-e^2)}{(1+e\ cos\ \nu)}$$

$$tan(\Theta - \Omega) = tan(\nu + \omega)\ cos\ i$$

$$\rho = r\ cos(\nu + \omega) sec(\Theta - \Omega)$$

Rectangular coordinates:

$$X = cos\ E - e \quad ; \quad Y = \sqrt{(1-e^2)} sin\ E$$

$$x = AX + FY \quad ; \quad y = BX + GY$$

Chapter 8
Orbit computation

Andreas Alzner

8.1 Introduction

Many methods have been given for the calculation of a visual binary orbit. The motion of the Earth can be neglected, but the measurement errors are much larger than errors in positions of planets, asteroids or comets. Therefore these methods are entirely different than calculating an orbit in our planetary system. The decision, whether to calculate an orbit or not may depend on the following considerations:

For the first calculation of an orbit:

- is the observational material good and complete enough to give a reliable value for the important quantity a^3/P^2?
- are there only few recent measurements and does the companion approach a critical phase of the orbit, so that a first preliminary result will attract the observer's attention to the pair?

For the improvement of an orbit:

- are there large (or growing) deviations between observed positions and calculated positions?
- will the new orbit give a significantly more reliable result for a^3/P^2?

Rating the observational material: With a strongly marked curvature, even a comparatively short arc may suffice to give a reliable orbit, provided that the observations are consistent, see the two "well determined" arcs.

Now have a look at the two 'undetermined' arcs. Even high precision measurements will not allow us to calculate a preliminary orbit. Any result will have to be graded 'undetermined'. Substantial revisions are to be expected, see the complete ellipses. In the example, the blue ellipse results in a mass seven times larger than the red one!

In the case of the first calculation of an orbit the observed arc will determine, which method should be used. If there is any hope that the observational material

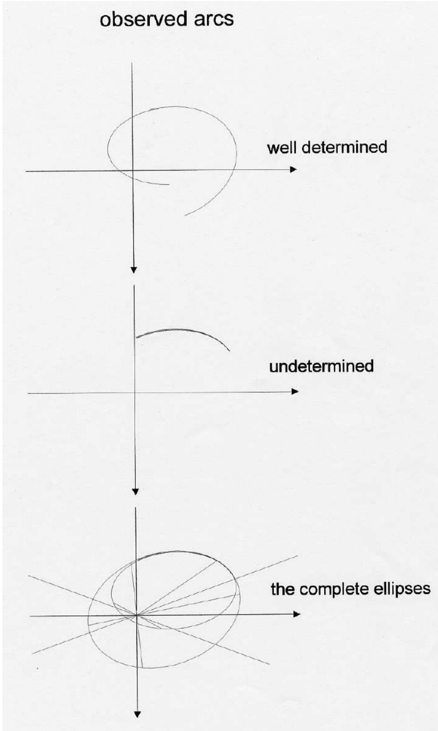

Fig. 8.1 Well determined arcs, undetermined arcs, the complete ellipses

will allow a least square fit applied to a set of provisional elements, a simple geometrical method is sufficient to obtain an initial set of elements. If the observed arc is undefined or too short to draw the complete ellipse, a dynamical method is required like the method by Thiele and van den Bos.

8.2 A simple geometrical method

The well observed orbit of $\Sigma 1356 = \omega$ Leo (plot from Mason and Hartkopf, 5th Orbit Catalogue, 1999) is used to illustrate a geometrical method. Elements (van Dessel 1976):
P = 118.227 years, T = 1959.40, $a = 0''.880$, e = 0.557, $i = 66^\circ.05$, $\omega = 302^\circ.65$, $\Omega = 325^\circ.69$ ascending.

First the apparent orbit is drawn manually. In the next figure the primary star is located in the centre O of the coordinate system, P is the periastron, A is the apastron, C is the centre of the ellipse, the line connecting the apastron and the

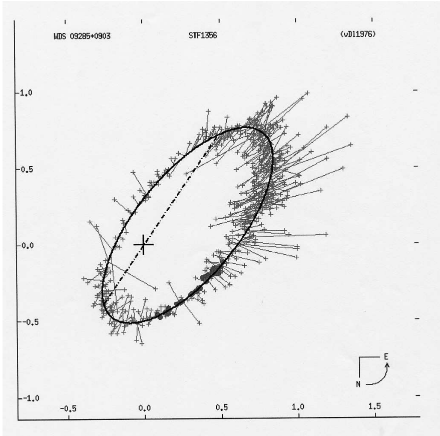

Fig. 8.2 Orbit of Σ1356 and observed positions

periastron is the projected semiaxis major, L and Q are the points, where the true anomaly is –90°and +90°.

The elements are found as follows:

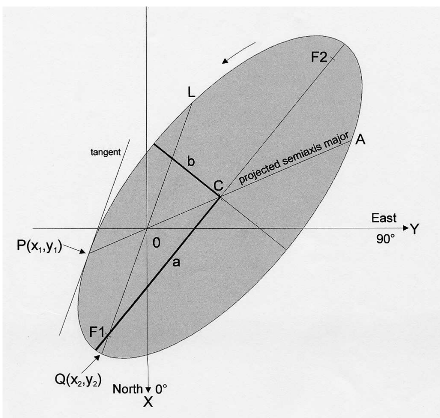

Fig. 8.3 Geometrical method

1. Draw the complete ellipse (the law of areas must be fulfilled). Construct the centre C of the ellipse. After periastron *P* is found, the eccentricity is calculated: *e* = CO / CP.

2. Draw the tangent in :first find the focal points F1 and F2 of the apparent ellipse. Draw the triangle F1 P F2. The straight line perpendicular to the line cutting the angle in P into halves is parallel to the tangent in P.

3. Draw the line L O Q: it is parallel to the tangent in P.

4. Determine the coordinates x,y of the points P(x_1, y_1) and Q(x_2,y_2).
5. The Thiele-Innes constants are calculated as follows:

$$A = x_1/(1-e) \quad ; \quad B = y_1/(1-e)$$

$$F = x_2/(1-e^2) \quad ; \quad G = y_2/(1-e^2)$$

6. Calculate the elements i, ω and Ω. The relations are:

$$tan(\Omega + \omega) = (B-F)/(A+G)$$

$$tan(\Omega - \omega) = (B+F)/(A-G)$$

$$a^2(1+cos^2 i) = A^2 + B^2 + F^2 + G^2$$

$$a^2 cos i = AG - BF = v$$

$$a^2 = u + \sqrt{(u+v)(u-v)}$$

7. Determine the period and the time of periastron from the observed positions. The areal constant c in the apparent ellipse is twice the area swept by the projected radius vector. a and b are the semiaxis major and minor of the apparent ellipse, respectively. The period is:

$$P = 2\pi\ a\ b/ \mid c \mid$$

Now the preliminary elements have to be corrected in a least square fit.

8.3 Differential correction of orbits

In this section the correction of an orbit for a visual double star by means of a least squares fit using the method of differential correction will be explained in detail. The process of calculation follows the formulae and advises given in ?Double Stars? (Heintz, 1967)4.

First of all, a misunderstanding should be avoided. Many people think, using ‘differential corrections’ means that only small corrections can be applied and that the start orbit must be very close to the final solution. This is not correct at all. When handling with care, quite large corrections can result or are possible, and the method is very powerful because only a limited number of orbits has to be calculated in order to get the final solution. During the approximation, the calculator can look at residuals and control the process of calculation. The procedure cannot be automized in many cases, especially if there are few measures or the measures are distributed over a part of the ellipse only.

In addition, the final solution of an orbit calculation does not depend so much on the method of calculation. It depends on the weights assigned to the observations. There was and is a lot of discussion concerning the weight to be given to visual measurements compared with photographic and speckle measurements. Only experience and comparison of measurements with definitive or very well determined orbits or with pairs in very slow motion can allow to determine reliable weights.

The mathematical rule for the calculation of a weight W is:

$$w \sim 1/\sigma^2$$

where σ is the error of the measurement.

Now, the formulae for the corrections have to be set up. We follow the principle, that a change dα_j of some coordinate α is composed of elements corrections dε_i given by the formula:

$$\sum_{\frac{(}{\partial\alpha_j}} /\partial\varepsilon_j)d\varepsilon_j = d\alpha_j$$

where the dα_j are the residuals and the dε_i are the improvements to be found. The quotients are calculated from initial elements found e.g. by the graphical method described in the previous chapter.

Heintz has given the following formulae when using polar coordinates. So, all differentials are expressed in units of degrees:

e = sin ϕ

dϕ = 57.296 sec ϕ de

dη = μ sec^2 ϕ dT

da$^\circ$ = 57.296 da/a

dm = N sec^2 ϕ dμ

The assumption is that all observations have been collected (corrected for precession) and a start orbit is available.

For each observational position (it may consist of the mean of several observations because of economy of calculation and is called a ‘normal position’) one has to calculate two Equations of Condition:

dΩ + B di + C dϖ + F dη + G dm + H dϕ = dθ

dα° + b di + cϖ + f dη + g dm + h dϕ = 57.296dρ/ρ

where dθ and dρ are the residuals for this observational position, i.e. dθ= θ (observed) - θ(calculated, using the start orbit) and dρ= ρ(observed) - ρ(calculated, using the start orbit).

The auxiliary functions are defined as follows:

ε = sec ϕ sin ν (2 + e cos ν)

ζ = sec ϕ (1 + e cos ν)^2

κ = - sec ϕ cos ν (1 + e cos ν)

λ = tanϕ sin ν (1 + e cos ν)

and the coefficients B, C, F, G, H and b, c, f, g and h become:

B = - $\cos^2$ (θ - Ω? - ?) tan (ν + ω) sin i
C = + $\cos^2$ (θ - Ω) $\sec^2$ (ν + ω) cos i
F = - ζ C
G = + ζ C t
H = + ε C
b = - sin2 (θ - Ω) tan i
c = - sin (θ - Ω) cos (θ - Ω) sin i tan i
f = - (ζ c + λ)
g = + (ζ c + λ) τ
h = + ε c + κ

Each equation of condition has to be multiplied with the square root of the weight which is assigned to this measurement (left side and right side!). For determination of the weights: see the suggestion by Heintz in 'Double Stars'(4), page 46 or Hartkopf et al: The weighting game in 'Binary star Orbits from Speckle Interferometry II'.7 For example, visual angle measurements obtain more weight than visual distance measurements.

Let's assume that there are 50 normal places, i.e. 50 times 2 Equations of Condition and let us continue with the equations for dθ.

There is a system of 50 linear equations with the 6 unknowns dΩ, di, dω . . . : On the left side there is a 50 x 6 matrix (let's call it A), on the right side a 50 x 1 vector (let's call it R1) containing the residuals.

Now the system of Normal Equations has to be set up by matrix multiplication:

$$(AT * A) * ca = AT * R1$$

where $\mathbf{A}^T$ is the transposed matrix of **A** and **ca** is the 6 x 1 - vector containing the unknown corrections:

$$\mathbf{ca} = \begin{pmatrix} d\Omega \\ di \\ d\omega \\ d\eta \\ dm \\ d\phi \end{pmatrix}$$

On the left there is a 6 x 6 matrix $\mathbf{A}^T * \mathbf{A} = \mathbf{a}$, on the right a 6 x 1 vector $\mathbf{A}^T *$ **R1 = ra**. This is the system of Normal Equations.

Solving such a system of equations is pre-programmed in most mathematical programs and gives the solutions for dΩ, di, dω, dη, dm, dϕ. But the procedure works only if the observed arc represents the orbit fairly well and when there are many good measurements. Otherwise, large and unreliable corrections will result.

Now the corrections have to be applied to the elements of the start orbit; this yields the new elements.

The same can be done for the system of linear equations for dρ to get the correction for a° and a, respectively. This gives us a 6 x 6 matrix **BT** $*$ **B = b** and a 6 x 1 vector **rb**. Differential corrections with matrix **b** work well only if there are many good measurements for the distance like for example in the case of a binary such as McA14Aa. (Indeed, McA14Aa can be corrected in rectangular coordinates also very well).

Is the corrected orbit better? This has to be checked for every new set of elements. For every new orbit one calculates the two sums of squared errors. We call it SUM:

$$SUM = \sum_{i}^{w} W_i.(obs - calc)^2$$

W_i = weight assigned to the i^{th} equation of condition, n = number of normal places. Two SUMs have to be calculated, one for the angles, the second one for the distances.

Important note:

It is very much recommended that the two 6 x 6 normal equations and residual vectors for θ and ρ are added together in order to get a 7 x 7 matrix c and a 7 x 1 residual vector **rc** for correction of all 7 elements simultaneously. For adding up the matrices and the vectors to get the 7 x 7 matrix **c** and the 7 x 1 vector **rc**, add zeros in this way:

$$\begin{bmatrix} a11 & 0 & a12 & a13 & a14 & a15 & a16 & ra1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ a21 & 0 & a22 & a23 & a24 & a25 & a26 & ra2 \\ a31 & 0 & a32 & a33 & a34 & a35 & a36 & ra3 \\ a41 & 0 & a42 & a43 & a44 & a45 & a46 & ra4 \\ a51 & 0 & a52 & a53 & a54 & a55 & a56 & ra5 \\ a61 & 0 & a62 & a63 & a64 & a65 & a66 & ra6 \end{bmatrix}$$

and

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & b11 & b12 & b13 & b14 & b15 & b16 & rb1 \\ 0 & b21 & b22 & b23 & b24 & b25 & b26 & rb2 \\ 0 & b31 & b32 & b33 & b34 & b35 & b36 & rb3 \\ 0 & b41 & b42 & b43 & b44 & b45 & b46 & rb4 \\ 0 & b51 & b52 & b53 & b54 & b55 & b56 & rb5 \\ 0 & b61 & b62 & b63 & b64 & b65 & b66 & rb6 \end{bmatrix}$$

Operating with **c** and **rc**, the algorithm is much more robust and unreliable excessive corrections happen less frequently.

In case the observed arc is short one can also delete individual columns from the normal equations in order to reduce the number of corrected orbital elements in one step. Some calculators for example vary the period P by a step-width of a certain amount and look for the corrections of the remaining elements. Normally, the whole procedure is an iterative one, and it may take about 5 to up to about 20 to 50 steps, depending on the observational material and the observed arc.

For checking the reliability of the programs, first generate two artificial orbits X and Y with somewhat different orbital elements. From orbit X ‘observation points’ are calculated and orbit Y serves as start orbit. If the program works properly the corrected orbit must become orbit X. The observation points (about 15 to 20) should be well distributed around the complete ellipse. For example:

X - orbit: P = 360, T = 1903, a = 0.70, e = 0.30, i = 131.5, omega=149.0, node = 120.0

Y - orbit: P = 340, T = 1900, a = 0.90, e = 0.35, i = 140.0, omega=140.0, node = 117.0

Although the two sets of elements differ considerably, the method of differential corrections will find the correct solution in 2 steps only. In practice, for real observations one will see: the less complete the observational material and the less accurate the observations, the more difficult the procedure. In case of a too undetermined arc (little curvature, periastron not observed or too far in the future etc.), the corrections may become very large and unreliable as mentioned above.

Possible ways to continue in such a case:

- Correct only 5 or 4 or even only 3 elements simultaneously.
- Do not try to correct at all, wait for new measurements.

Some calculators do it in the following way: They vary P, T and e in a 3 dimensional grid (fixed values) and correct the remaining elements thus calculating hundreds or even thousands of orbits and as many values for the 2 SUMs of residuals.

Calculations of errors of orbital elements can be performed if the observed arc contains the 2 ansae and hence defines the orbit already well:

Calculate the inverse of the 7 x 7 matrix c, this gives c−1. The diagonal elements are $c_{11}{}^{1}$, $c_{22}{}^{1}$, ... $c_{77}{}^{1}$

Calculate the sum of the residuals:

$$\sum + \sum W.\theta_i.(\Delta\theta^2) + W\rho_i.(\Delta\rho^2)$$

Now, the errors for the orbital elements can be calculated:

$$d\Omega = \sqrt{\frac{\Sigma}{n-7}.c_{11}{}^{-1}}$$

$$da = \sqrt{\frac{\Sigma}{n-7}\cdot\frac{a^2}{57.296}.c_{22}{}^{-1}}$$

$$di = \sqrt{\frac{\Sigma}{n-7}.c_{33}{}^{-1}}$$

$$dT = \sqrt{\frac{\Sigma}{n-7}\cdot\frac{1}{\mu^2(sec^2\phi)}.c_{55}{}^{-1}}$$

$$d\mu = \sqrt{\frac{\Sigma}{n-7}\cdot\frac{1}{sec^2\phi}.c_{66}{}^{-1}}$$

$$de = \sqrt{\frac{\sum}{n-7} \cdot \frac{1}{57.296^2.(sec^2\phi)^2}.c_{77}{}^{-1}}$$

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Chapter 9
Some famous double stars

Bob Argyle

9.1 Introduction

In this chapter we move out from the Sun and look at some of the neighbouring double and multiple stars which have been observed for centuries. In some cases there are still secrets to be revealed. The beauty of a sunset on Earth has inspired poets and artists for millennia - what must it be like when there is not one sunset but two or more with each sun glowing in a different colour. The chiaroscuro would be impressive to say the least. Not all double and multiple systems have different colours - some contain stars of essentially the same spectral class and therefore colour.

9.2 Mizar and Alcor

This brightest of naked-eye double stars was known in antiquity and attracted the attention of the early telescopic observers. Alcor (mag 4.2) is 11.8 arc minutes distant making the pair easy to see. In 1617 Castelli noted that Mizar, the brightest of the two stars (V=2.0) was again double and so Mizar has the distinction of being the first double star discovered at the telescope.

Bradley, in 1755 was the first to measure its relative position at 143.1, 13".9. Lewis (1) using positions up to 1903 found that the annual motion in position angle was $+0^{\circ}.025$ and from this estimated a period of 14,000 years. The physical connection between Mizar and Alcor was established when the proper motions were found to be similar. In fact, there is a greater connection since a number of the other bright stars in the Plough are moving through space in a loose association - the nearest star cluster to us, in fact twice as close to us as the Hyades. The exceptions to this are α and η.

In 1857 Mizar emerged into prominence once more as it became the first double star to be imaged photographically. Bond used the 15-inch refractor at Harvard

College Observatory for this purpose. Agnes Clerke (2) quotes ”Double star photography was inaugurated under the auspices of G. P. Bond, Apr 27, 1857 with an impression, obtained in eight seconds, of Mizar, the middle star in the handle of the Plough”

With the advent of photographic spectroscopy, plates of Mizar A taken at Harvard College Observatory in 1886 showed that the Calcium K line leading to an announcement by Pickering in 1889 (3). Mizar A had also become the first spectroscopic binary to be found, beating the discovery of Algol (4) by a few months. In 1906 Frost (5) and Ludendorff (6) independently announced that Mizar B was also a spectroscopic binary, this time a single-lined system of low amplitude making radial velocity measurements rather difficult. The period was not determined correctly until relatively recently when Gutmann (7) found a value of 175.5 days.

In the 1920’s with the 20-foot stellar interferometer Frederick Pease (8) carried out two sets of observations, in April 1925 and May/June 1927, calculating a period of 20.53851 days for the orbit of Mizar A.

The Hipparcos satellite showed that the parallax of Mizar is 41.73 mas whilst that of Alcor is 40.19 mas corresponding to distances of 23.96 and 24.88 parsecs thus giving a formal difference in the distance to the two stars of about 3 light years.

In the 1990’s the spectroscopic pair Mizar A became one of the first stars to be observed using the Mark III optical interferometer on Mount Wilson in California. An improved instrument, the Navy Prototype Optical Interferometer (NPOI) was then constructed in Arizona. A product of the collaboration between the United States Naval Observatory, the Naval Research Laboratory and Lowell Observatory the instrument uses phase-closure to build up an optical image of the two components. An interesting consequence of observing pairs with such short periods is that the orbital motion over one night is substantial and has to be allowed for. The NPOI data is more accurate than that from the Mark III and allows the dimension of the orbit to be determined without an independent measure of parallax.

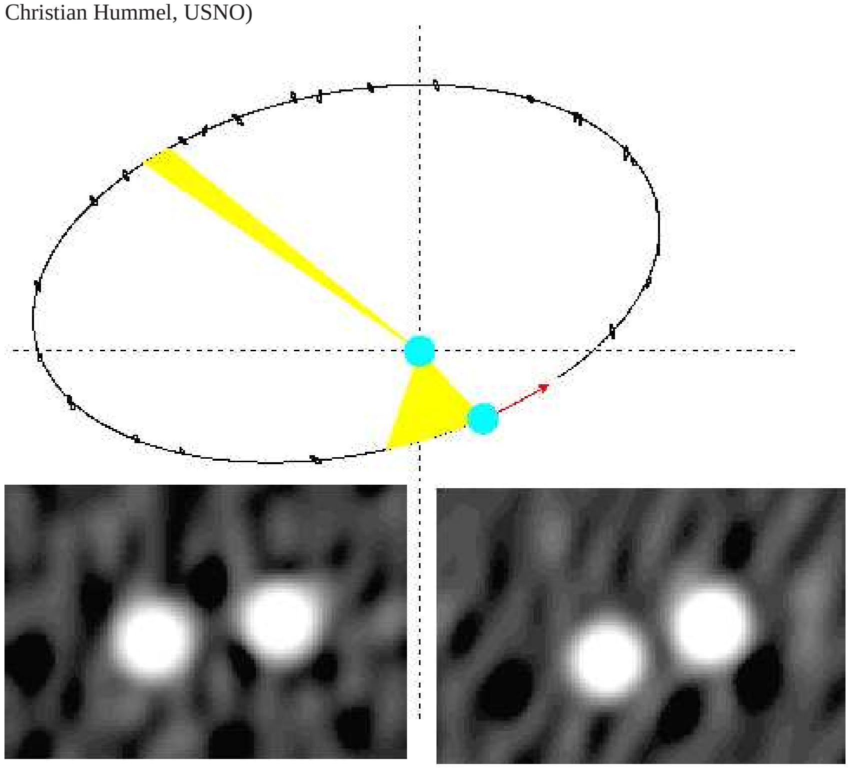
The orbit was found to have a semi-major axis of 9.83 mas and the maximum observed separation was 11 mas and the minimum 4 mas. Combined with the data from the spectroscopic orbit, the masses have been determined with great accuracy. The distance has also been derived since both the linear and angular sizes of the orbit are known.

In 2010, Mamajek and colleagues(8a) using the 6.5 meter MMT found that Alcor has a low-mass companion $1''.11$ distant and probably 0.3 M sun. It is an active star which accounts for the X-rays observed from Alcor. The discovery was made independently by Zimmermann et al (8b). the Mizar/Alcor system now consists of three pairs of binaries so its very similar to Castor but on a grander scale.

9.3 Castor

Possibly found by G. D. Cassini in 1678, the brilliant white leader of Gemini was certainly known to be a double star in 1718 when Pound noted the position angle

Fig. 9.1 The components of the 20.3 day spectroscopic binary Mizar showing motion over a 24 hour period (below). Above is plotted the apparent orbit from NPOI observations. The minimum separation is 4 mas. Note the size of the error ellipse for each observed point. (Courtesy - Dr. Christian Hummel, USNO)



by projecting the line between the two stars and referring it to lines drawn to the nearby bright stars. In 1722 he repeated the observation and a significant change had occurred. Sir John Herschel evaluated this and found that the PA had decreased by more than 7° .

Castor is the pair which Sir William Herschel first used to demonstrate his theory that the motion between the two stars is due to a physical attraction.

In the 19th century the large numbers of observations of Castor by double star observers led to a plethora of orbits with periods ranging from 250 to more than 1000 years. As the pair had not then passed periastron, or even defined one end of the apparent ellipse this was all preliminary. Even today, several orbits give similar residuals and the period would seem to be of order 450 years. A third star of magnitude 11, Castor C, located at 164° and 71″ (2000) and originally thought to be of use for measuring the parallax of AB is actually moving through space with Castor and is part of the system.

In 1896 Belopolsky showed that Castor B was a single-lined spectroscopic binary whilst Curtis at Lick Observatory (9) showed that the same applied to the A component. In 1920, Adams and Joy (10) announced that Castor C was also a short period spectroscopic binary but in this case it was double-lined and it also turned out to be an eclipsing system and is now known as YY Gem.

Castor is a relatively nearby system and Hipparcos determined a parallax of 63.27 mas equivalent to a distance of 15.80 parsecs or 51.5 light years. From this and the semi-major axis of the orbit one can estimate the real size of the true orbit of Castor AB. The maximum separation of the stars is about 130 AU, some 4 times the distance of Pluto from the Sun.

Although the bright components A and B are single-line spectroscopic systems, it was originally assumed that the stars in each system were similar in spectral type. Recent observations of x-ray emission from all three visible stars in the Castor system have proved that the companions to A and B are late-type stars, a conclusion borne out by the distribution of masses in the system. The total mass of the Castor AaBb quadruple is 5.6 Msun. This is made up of Castor Aa (spectral types A1V and K7V and masses 2.6 and 0.7 Msun) and Castor Bb (spectral types A1V and M0V and masses 1.7 and 0.6 Msun). Star C which is the eclipsing variable YY Gem is also extremely active in X-ray and radio wavelengths and it is thought that the surfaces of both components are covered in star spots. Its two components are dwarf stars of spectral class M1. A recent paper by Qian (11) speculates that a weak periodic variation in the period of YY Gem may be due to a perturbation by either a brown dwarf or giant planet or it may also be due to magnetic activity so further research is needed.

Castor, like Mizar, is also part of a moving group that contains 16 other stars including the first magnitude objects Vega and Fomalhaut.

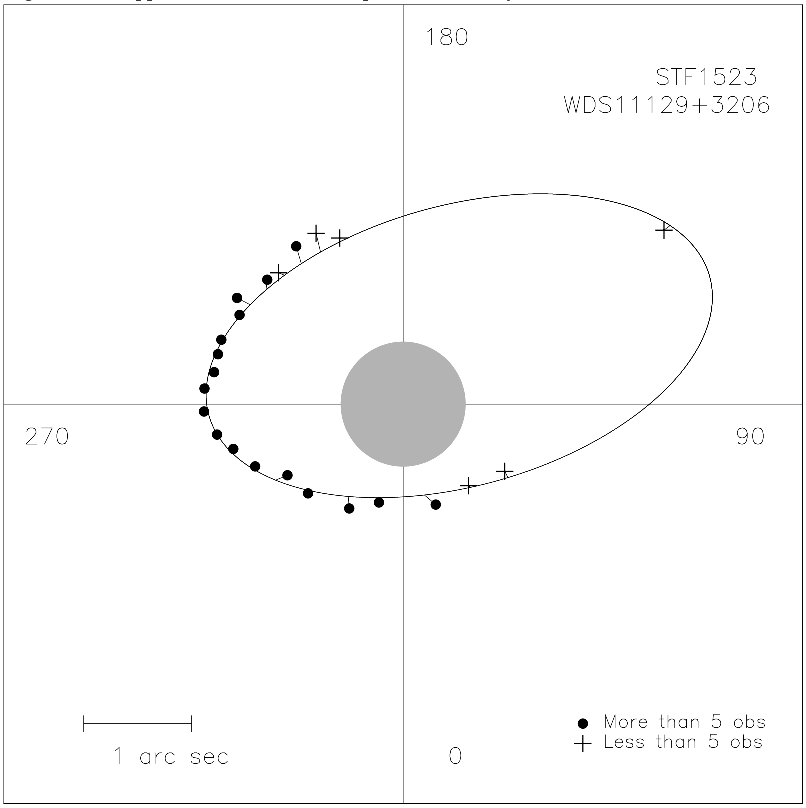
Fig. 9.2 The apparent orbit of Castor, period = 445 years. In this and subsequent figures the radius of the central circle represents the Dawes limit for a 20-cm aperture.

Two current orbits which give small residuals from recent observations show the pair widening for about 80 - 100 years before it reaches a maximum distance of about 8 arc seconds early in the 22nd century. It will thus remain an easy and beautiful object in small telescopes for many years to come. Figure 9.2 shows the apparent orbit of AB.

9.4 xi UMa

This beautiful pair of yellow stars was discovered by William Herschel on 1780, May 2 when he wrote “A fine double star, nearly of equal magnitudes, and 2/3 of a diameter asunder; exactly estimated”. From the latest orbital elements, we can deduce that the separation on that date was 2.3 arc seconds. As Herschel was describing the separation between the disks rather than the disk centres we can see that the images in his telescope must have been about 1.4 arc seconds across. The subsequent, rapid orbital motion convinced Herschel that the stars were genuinely connected and in 1827 Savary (12), in France, made the first orbital analysis of any

Fig. 9.2 The apparent orbit of xi UMa, period =59.878 years

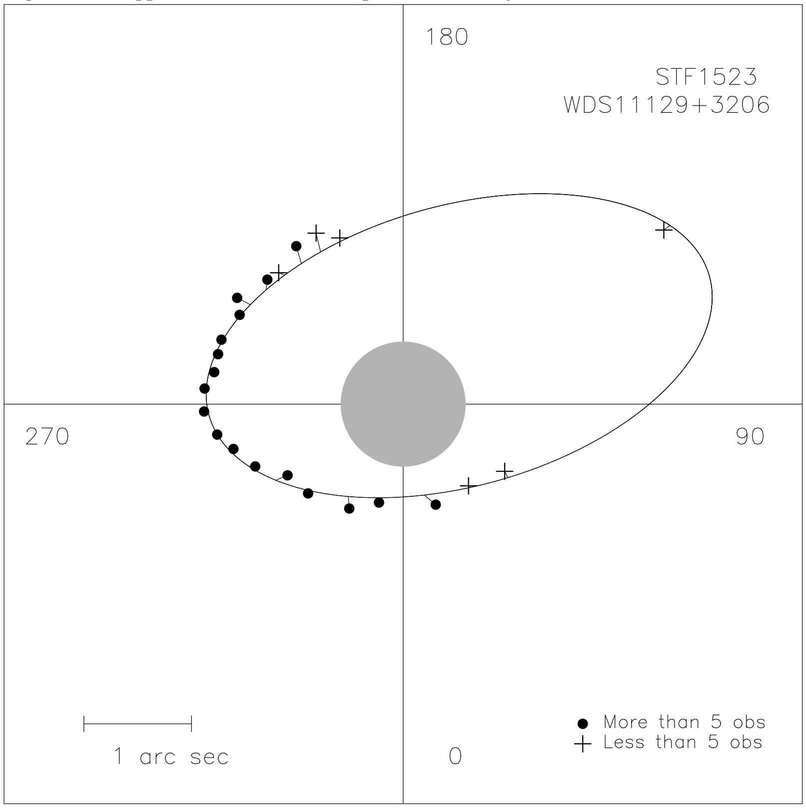


double star using xi UMa for the purpose. He obtained a period of 58.8 years and an eccentricity of 0.41. This compares with today's latest values of 59.9 years and 0.40.

As was the case with 70 Oph (see following), the ease of measurement of the pair and the relatively short period led to a plethora of orbits. At the beginning of the last century the separation of the pair was over 2 arc seconds and increasing, so taking spectra of both components became possible in good seeing. Norlund (13) found a small periodic perturbation in the residuals of the orbit of star A with a period of 1.8 years. As dark companions were somewhat in vogue at the time it seemed natural to ascribe this as the cause of this effect. At this time Wright, at Lick Observatory had already noted radial velocity changes corresponding to this 1.8 year period in the spectrum of A. Eventually an orbit was computed by van den Bos (14) which is still used today.

Although spectral plates were also taken of star B from 1902 it was not until 1918 that it, too, was found to be a spectroscopic binary with a period of just under 4 days. Berman (15) produced an orbit for Bb which remained the sole analysis until

Fig. 9.3 The apparent orbit of xi UMa, period =59.878 years



Griffin revisited the system (16). He was able to show that Berman's orbit required little adjustment, the difference in the period being 0.6 second! With each successive orbit, the period can be fixed with greater and greater certainty, if the periastron passage is sharply defined. Since Berman's analysis, the pair Bb had gone through more than 6,000 orbits.

The next development came much later during an investigation of the system by Mason et al. (17) at CHARA (Georgia State University). By using speckle interferometry measures they were able to obtain very accurate relative positions and these were used in an attempt to tune the orbital elements of the AB pair to give a more precise value of the individual masses (1995). The results of these observations are shown in Fig 1 and actually show the 1.8 year perturbation in Bb in its orbital motion. During the course of their observing campaign, Mason et al. observed yet another component, attached to the Bb subsystem but it appeared in only 1 out of 27 observations.

A later discussion by Daniel Bonneau (18) argues that if this new component exists, it would have a mass of about 0.5-0.7 sun and the orbital inclination of the B system would then be incompatible with both the rotation of B and the coplanarity of the orbit Bb. Resolution of Bb will only be possible from a ground-based interferometer systems although Aa should be resolvable in a 2.5-metre telescope with infra-red adaptive optics.

9.5 70 Oph

Discovered by William Herschel in 1779, this pair has been a favourite amongst double star observers of all kinds ever since. Its proximity to the Sun (16.6 light years according to Hipparcos) means that during the orbit of 88 years the separation of the stars varies from 1.5 to 6.5 arc seconds, and it is thus possible to follow it through its whole orbital cycle with ease. The recent periastron passage in 1984 showed the companion moving almost 20 degrees over the year. Another reason for its popularity is the beautiful contrast between its unequal components which have given it a prominent place in all observing handbooks. Placed near the equator it can be seen from virtually all latitudes.

Thomas Lewis in his book on the Struve stars said in 1906 “It is a splendid system and quite worth the time spent on it by Observers and Computers, although it is a source of much trouble to the latter”. Surprisingly enough, it was only recently that the agreement between the spectroscopic and visual orbit was regarded as satisfactory.

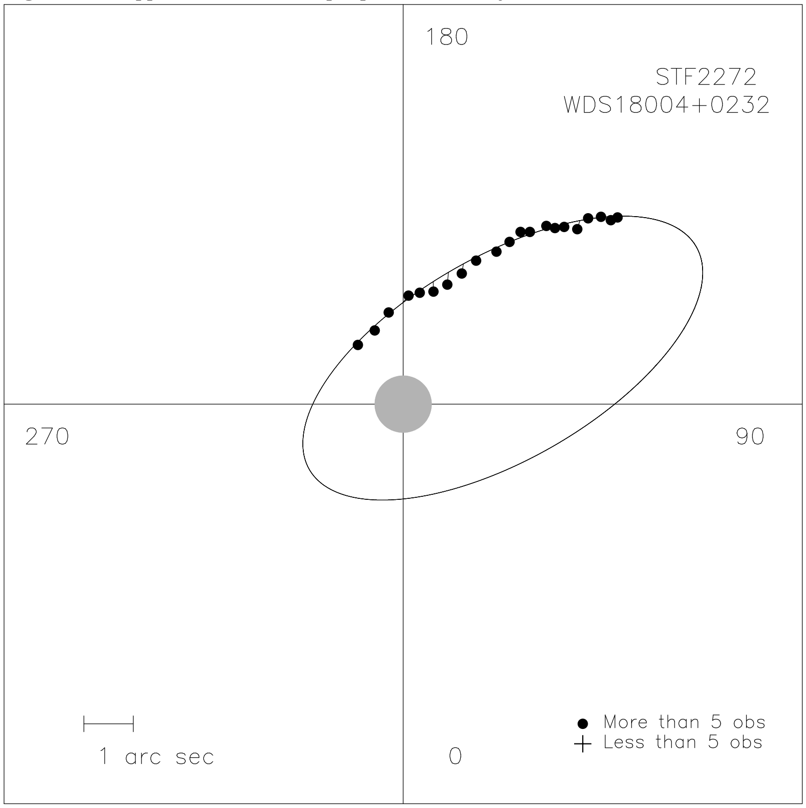
70 Oph was a very popular object with Victorian observers and so measures were numerous. As the pair is an easy object disquiet was expressed about the way that the observed measures were not agreeing with the predicted values from the various and numerous orbits that were being calculated (Lewis lists 22). In 1896, T. J. J. See (19) postulated that these disagreements were due to the presence of a 3rd body orbiting one of the stars in the system. In 1906 Lewis dedicated a large amount of time and space in his volume to discussing the pair. He was convinced that the anomalies were due to a 3rd body orbiting star B and even derived a period of 36 years for it. Burnham, in his catalogue, dismissed the idea saying it was merely observational error but the idea persisted. Pavel (20) postulated a companion orbiting A with a period of 6.5 years.

In 1932, Berman using radial velocity measurements of plates taken at Lick Observatory, found a cyclical trend with a period of 18 years but many years later Berman said that he had ceased to be convinced of this result (21).

Reuyl and Holmberg (22) at McCormick Observatory found an astrometric perturbation with an amplitude of 0.014 arc secs from a series of plates taken between 1914 and 1942.

Worth and Heintz (23) re-visited the visual measures and also produced a trigonometrical parallax for the star. Although there were some problems with measures in the 1870’s they could find no evidence for a 3rd body other than a rather unlikely scenario of the passage of a 3rd body through the system at that time.

Fig. 9.4 The apparent orbit of 70 Oph, period = 88.38 years



Heintz computed the orbit afresh in 1988 (24) and summarised the situation at the time. This was that recent radial velocity measures showed no perturbation and modern measures using long-focus photography show no systematic deviations beyond the 0.01 arc second level.

Batten and Fletcher (21) re-examined the radial velocity material measured by Berman and could not find his periodic component in the velocities. However they came to the conclusion that the quality of the early plates means that large residuals ’are not of much significance’. The re-determination of the spectroscopic period came out at 88.05 years and agrees with Heintz’ visual orbit within the quoted error (0.70 year).

The WDS catalogue lists 15 faint, optical companions ranging from visual magnitudes 10.6 to 16. None of these appear to be related physically to 70 Oph AB which has quite a high annual proper motion (″ per year). More recently, in an attempt to look for sub-stellar companions,deep IR imaging with the Hale 5-metre telescope in 2004 led to the discovery of 2 faint companions both within 10″ of

70 Oph A. It is not yet clear whether these objects share the proper motion of the binary. More astrometry is needed.

9.6 zeta Cnc

The history of this fascinating multiple star has recently been comprehensively reviewed by Roger Griffin (25) but a brief summary is worth including here. Whilst the duplicity of the star had been taken to originate with Tobias Mayer who observed it in 1756, Griffin has shown that the first suspicion that the star was double comes from an observation by John Flamsteed on 1680, Mar 22. Flamsteed refers to ”the north-following component” which agrees nicely with the position of the brighter of the two stars at that time. The separation of the two stars at the time was about 6 arc seconds.

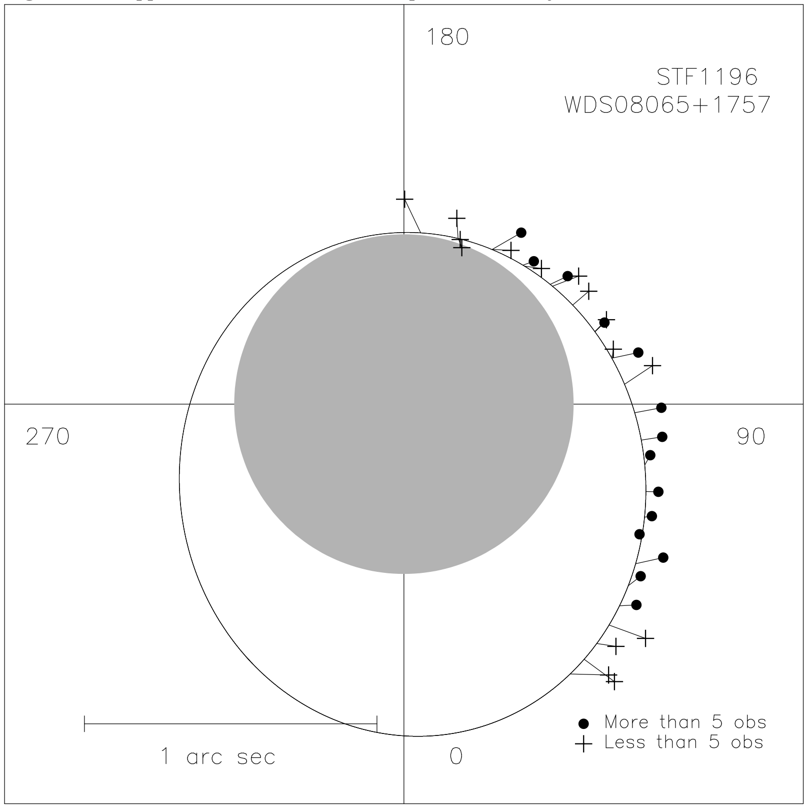
In 1781 November William Herschel divided the bright component into two and catalogued the close pair as H I 24. (Herschel allocated a class for pairs of differing separations ranging from I for pairs closer than 2 arc seconds out to VI for pairs divided by 32 arc seconds or more). His notes on the position angle allow a value of 3.5 degrees to be assigned to the system. The close pair was not observed again until 1825 when Sir James South measured it from France when the position angle was given as 58 degrees. It was only when later measures showed that the position angle was actually decreasing that it became clear the close pair had moved through 305 degrees since 1781!

Over the next twenty years or so, growing numbers of double star observers made copious measures of both the close and wide pair and the motion of star C around AB was clearly not proceeding in a smooth curve. The position angle would reduce smoothly and then for several years it would stay constant and then resume its course. In 1874 Otto Struve considered the results of almost 50 years of measures by his father, F. G. W. and himself. His conclusion was that the ’wobbling’ of C was due to the presence of a fourth star D rotating around it with a period of about 20 years. Towards the end of the C19, Seeliger produced a comprehensive analysis of the motions in the zeta Cnc system. His astrometric orbit for the pair CD was remained in force for over 100 years.

Whilst the existence of star D was in no doubt, few sporadic efforts were made during the last century to detect it. In 1983, D. W. McCarthy (26) using an infrared speckle interferometer announced that he had detected not only star D but yet another component, in other words, the main sequence component C, a white dwarf and another star. This detection was never confirmed and there the matter stood until the early months of 2000.

Using an adaptive optics system working in the infra-red on the Canada-France-Hawaii telescope on the island of Hawaii, J.B.Hutchings and R.F.Griffin (27) produced the first direct image of star D. It is a very red object but the effect it has on star C suggests a comparable mass to C and thus D itself probably comprises a pair of M dwarf stars.

Fig. 9.5 The apparent orbit of zeta Cnc AB, period = 59.56 years



The story does not end here however. In 2000, A. Richichi (28) reports on the observation of a re-appearance of zeta Cancri in the 1.52m telescope at Calar Alto on 1998, December 7. Working in the infra-red with a broad-band K filter the occultation trace showed 4 definite stellar sources and slight but significant evidence for a 5th star, located some 64 mas from star C. Referred to as E it would appear that it is another low mass M dwarf possibly with a period of 2 years. The component seen by Hutchings and Griffin, D, was also easily visible but if double the separation is likely to be no more than 30 mas thus requiring a considerably larger aperture to resolve it.

9.7 References

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Chapter 10
The resolution of a telescope

Bob Argyle

10.1 The Airy disk

The structure of an image formed by a circular aperture was first formulated by George Airy in 1835. In a refractor, the effect of diffraction on the image of a star in the focal plane is to produce a series of faint concentric rings around a central star disk, the Airy disk.

The Airy disk has a normalized (the central peak is scaled to one) intensity pattern given as:

$$I_{\mathrm{Airy}}(\rho) = \left(\frac{2J_1(\alpha\rho)}{\alpha\rho}\right)^2, \tag{10.1}$$

where ρ is the radial distance, $J_1(\alpha\rho)$ is the Bessel function of the first kind of order one (of $\alpha\rho$), $\alpha = (\pi D)/(\lambda f)$, D is the diameter of the aperture, λ is the wavelength, and f is the focal length of the optical system. This diffraction pattern arises as a result of the aperture being circular and having a sharp edge.

To calculate values using Bessel functions, one usually has to resort to numerical techniques. For use here, it is only necessary to know the value at which $J_1(\alpha\rho)$ goes to zero for the first time – the first null. This happens when $\alpha\rho = 3.832$. Therefore, the diameter of the central peak of the Airy disk is given as:

$$\begin{aligned} D_{\mathrm{Airy}} &= 2\rho \\ &= \frac{(2)(3.832)}{\alpha} \\ &= (2.44)\frac{\lambda f}{D}. \end{aligned} \tag{10.2}$$

Looking at a star, most of the light (84%) goes into this central disk inside the first dark ring. The intensity of the first bright ring is 7% of the total light contained within the star image. The second bright ring is only 3% of the total light with the remaining 6% being distributed in the outer rings.

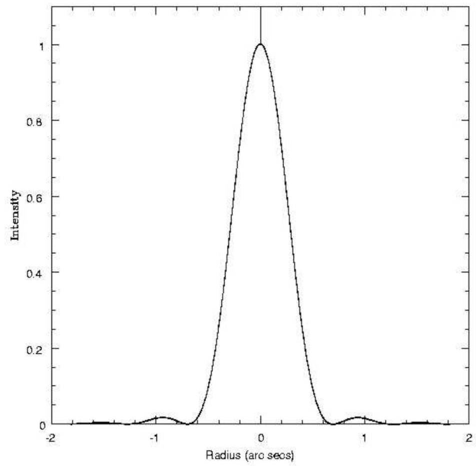

Fig. 10.1 The diffraction limited image of a star in a perfect refractor

10.2 The Rayleigh criterion

The theoretical diffraction image, or Airy pattern, of a star, seen in the focal plane of a perfect refracting telescope of aperture D cm is given by the pattern in Fig 1. If a second star, equally bright, and close to the first is also present then two Airy disks and sets of rings are visible.

The Rayleigh criterion is defined as the separation at which the peak of one Airy disk corresponds exactly to the centre of the first dark ring of the other profile. At this point the intensity in the dip between the two profile peaks drops to 73.5% of the intensity of either peak. In terms of the angular separation of the two stars this is given by 1.22 λ/D in radians.

Mathematically:

$$\tan(\theta_{\text{res}}) = \frac{(0.5)D_{\text{Airy}}}{f} = (1.22)\frac{\lambda}{D}. \tag{10.3}$$

Because θ_{res} is a small angle, $\tan(\theta_{\text{res}}) \approx \theta_{\text{res}}$ and

$$\theta_{\text{res}} = (1.22)\frac{\lambda}{D}. \tag{10.4}$$

but remember that θ_{res} is an angle in radians. To convert to seconds of arc, multiply by 206265.

The power of an objective to separate double stars therefore nominally depends on both the wavelength and the diameter of the objective. For the normal eye the wavelength is that of the peak reponse which is usually at 550 nm. So replacing λ in the last expression and converting from radians to arc seconds gives the Rayleigh criterion of 13.8/D where D is in cm.

Thus, for a 10-cm refractor, the Rayleigh criterion is 1.38 arc seconds. This corresponds to a drop in intensity of 30% in the centre of the combined profile, between the two maxima. However it is possible to see double stars still resolved even if they are closer than this limit. This was first demonstrated, for small telescope at least, by the Reverend William Rutter Dawes (1799-1868). Dawes says " ...I examined with a great variety of apertures a vast number of double stars, whose distances seemed to be well determined, and not liable to rapid change, in order to ascertain the separating power of these apertures, as expressed in inches of aperture and seconds of distance. I thus determined as a constant, that a one-inch aperture would just separate a double star consisting of two stars of the sixth magnitude, if their central distance was $4''.56$; - the atmospheric circumstances being moderately favourable"

Aitken, in his book 'The Binary Stars', points out that it is generally accepted that resolving power rests partly upon a theoretical and partly on an empirical basis. This can be seen in Figures 2 and 3. In the first, the Rayleigh criterion for a 20-cm refractor is shown with the intensity between the two peaks dropping to 73% of the maximum when the peak of one profile is 0.69 arc seconds from the centre of the second profile. Figure 3 shows the situation with Dawes limit demonstrated (the stars are 0.58 arc second apart in this case). The dip between the peaks is only 3% in this case. The resolution of a double star can therefore depend on the brightness of the stars as it is easier to see a small dip in a bright image than in a faint image.

10.3 The Dawes limit

As we have seen, Dawes arrived at this relationship in 1867 after tests with a large number of apertures over a number of years. Of course, Dawes only had the experience of refracting telescopes and unfortunately was not able to comment on the application of this relationship to reflectors, let alone modern catadioptric telescopes! In the next chapter, Christopher Taylor will argue that Dawes limit applies equally to reflectors at least to apertures of 30-cm.

Table 1. Dawes limit for various apertures

Although the Dawes limit is an empirical limit which happens to work well for small apertures (below about 30-cm) it was clear at the turn of the last century when Aitken and Hussey were using the large American refractors that it was not a universal limit. In 1914, Thomas Lewis (2) produced a number of other relationships beween aperture and separating power which, he said, were more relevant to cases where the stars were either unequally bright or both faint.

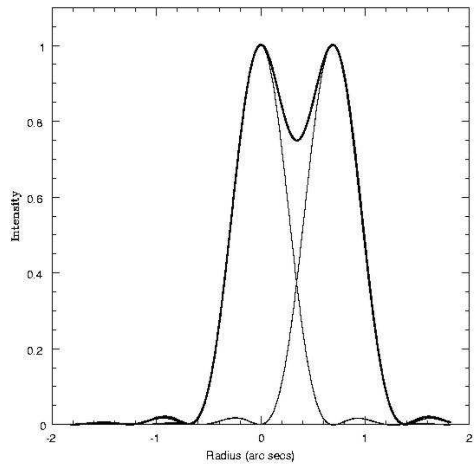

Fig. 10.2 Image profiles at Rayleigh limit

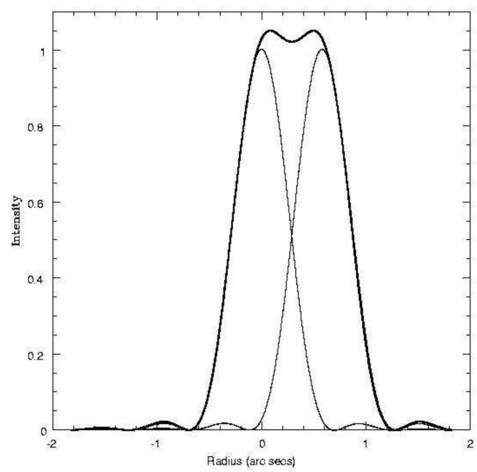

Fig. 10.3 Image profiles at Dawes limit

Table 10.1 Dawes and Rayleigh limits for various apertures

Aperture (in)	Aperture (cm)	Dawes limit arc secs	Rayleigh limit arc secs
1	2.5	4.56	5.43
3	7.6	1.52	1.82
6	15	0.76	0.92
8	20	0.57	0.69
10	25	0.46	0.55
12	30	0.38	0.46
16	40	0.29	0.35
24	60	0.19	0.23
36	91	0.13	0.15

10.4 The effect of magnification

The term resolving power is rather misleading as it implies that the amount of resolution depends on the magnification which it does not. A more accurate term might be the limit of resolution or the angle of resolution. If the two images appear separate in the eyepiece then an increase of magnification should separate the images still further assuming that the atmosphere will allow higher magnification.

The resolution of the human eye depends on the diameter of the pupil which can vary from 1.5mm to 8mm depending on the individual and conditions of illumination. For double stars it is generally accepted (Sidgwick, Nicklas) that the limiting resolution is about 2 to 2.5 arc minutes, lower than might be expected from the pupil diameter but when the eye is fully dark-adapted, the image definition is impaired by inherent aberrations in the eye.

In terms of measuring close pairs, Couteau (4) defines a resolving magnification which makes the radius of the first dark ring equal to the visual limit for the average eye. This magnification is numerically equal to the diameter of the objective in mm, i.e. m_r = 200 for an 20-cm telescope. Couteau considers that the minimum useful magnification for double stars is $2m_r$, or x400 for a 20-cm.

10.5 The effect of central obstructions

When a reflector or a Schmidt-Cassegrain is considered the resolution is slightly changed by the presence of the secondary mirror. The result is to slightly reduce the size of the Airy disk and reduce the radii of the bright rings, at the same time slightly broadening the width and increasing the intensity of the rings. The result is that for equal pairs, the reflector is as effective as the refractor until the central obstruction is greater than about 33%; but for unequal pairs the wider diffraction rings makes it more difficult to see faint stars close to bright ones. Christopher Taylor who will go into this in more detail in the next chapter which will deal with the effect of alignment and aberrations on resolution for Newtonian reflectors.

10.6 Using aperture masks

As we have seen above the circular form of the telescopic image is due to the shape of the diffracting aperture. The effect of the secondary mirror of a reflector modifies the size of the Airy disk and the radius and intensity of the diffraction rings.

The use of an aperture mask has been applied in several ways to modify the imaging of a telescope to deal with particular problems in imaging double stars, in particular with binary stars such as Sirius where the companion star is very much fainter than the primary, 10,000 times as faint in fact. Unless Sirius B (also called The Pup) is near its widest separation (about 11 arc seconds) it is impossible to see visually with a small telescope. This is because the glare from Sirius A spreads out to envelop the companion star.

One means of reducing the glare is to use a hexagonal aperture mask, a fact that seems to have been discovered by Sir John Herschel. The effect is to produce a six-pointed diffraction pattern, with most of the light being directed into these spikes and the sky between the spikes, relatively near the brilliant primary star being much darker than without the mask. E. E. Barnard used this method to measure Sirius B. By rotating the mask around the optical axis, it can be used to glimpse faint companions at any position angle to bright stars.

Another form of aperture mask is the coarse diffraction grating. Used by professional astronomers to reduce the large magnitude differences found in double stars the grating can also be used as a basis of a simple micrometer, the principle and operation of which can be found in Chapter 14.

Experiments have been made with other shapes of aperture masks. G. B. van Albada describes the use of an objective mask made from several lentil-shaped slits which were used in double star photography on the 23.5-inch refractor at Lembang in Java. It was possible to just record the companion of Procyon (a considerably more difficult pair that Sirius B) using this method.

A new application of this principle is being considered for imaging extrasolar planets close to bright stars. Whilst a sharp aperture produces a fuzzy image, it turns out that the converse is also true. By using a square aperture with a fuzzy edge, thus directing most of the light into four diffraction spikes at right angles to each other, NASA astronomers hope to find planets by direct imaging. The process of producing a fuzzy aperture is analogous to apodizing where by coating a lens with a film which is progressively more thick towards the outer edge, the effect on the Airy disk is to increase it in size but the diffraction rings are suppressed. A fuzzy-square mask should make it possible for telescopes to see Earth-like planets about five times closer to their star than with an ordinary telescope,

10.7 Below the Rayleigh limit

Airy's definition does not mean that closer pairs than this cannot be seen. In fact, elongations of the image can be followed down to a fraction of the resolving power. Simonow has tabulated the relationship between the shape of the image and the angular separation as the latter drops further below the nominal resolving power. For the 23.5-inch refractor at Lembang (Rayleigh criterion, R = $0''.23$) he came up with the following:

Just separated:	$0''.23$ = 1.00R
Notched:	$0''.21$ = 0.95R
Strongly elongated:	$0''.19$ = 0.86R
Elongated:	$0''.17$ = 0.77R
Slightly elongated:	$0''.15$ = 0.68R
Elongation suspected:	$0''.14$ (minimum distance estimated)

Thus Simonow was able to detect duplicity for pairs whose separations were about 0.7 of the Rayleigh criterion. Simonow extended his discussion of resolving power to include other combinations of magnitude and magnitude difference.

Paul Couteau has also discussed this subject in depth and obtains slightly smaller figures than Simonow for the 50-cm Nice refractor. He claims that the limit at which stars can be seen as double is 0.14 arc secs or half of the Rayleigh limit for this aperture.

An investigation into this by the writer has produced the graph in Fig 2 which shows the least angular separation at which close double stars in various apertures have appeared to be just distinguishable from a single image and it shows a surprisingly good correlation from the smallest to the largest aperture considered.

For a list of close pairs suitable for testing the resolution of a telescope see the Tables in Chapter 2. A more complete list can be found at the Webb Society web site `(http::/www.webbsociety.org/doublest01.html`.

10.8 Small apertures

Jerry Spevak, who observes from Canada has recently carried out an investigation into the resolution limit of a small telescope using double stars from the Hipparcos and Tycho catalogues. He worked through the pairs without advance knowledge of Δm and exact separation with the catalogue being checked only after noting the appearance of close pairs.

He found that the images of double stars can be divided into four categories, depending on separation: separate, touching, notched and elongated. These classifications are fairly self-explanatory. Examples of close pairs are given below along with the observed appearance and relevant data from Hipparcos.

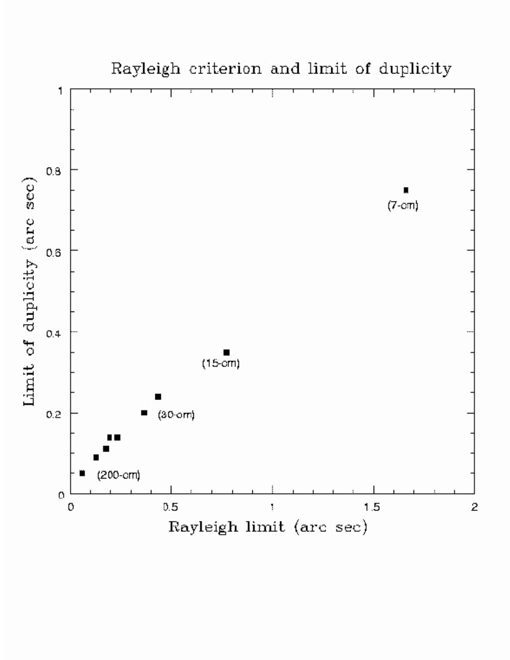

Fig. 10.4 Plotting Rayleigh limit against the limit of duplicity

Table 10.2 Observations by Jerry Spevak with a 70-mm refractor

Pair	MaGS	Separtion	Images
$\Sigma 65$	8.0, 8.0	$3''.1$	separate
$\Sigma 1905$	9.1, 9.2	$3''.0$	separate
$\Sigma 1284$	8.2, 9.7	$2''.5$	separate
$\Sigma 2845$	8.1, 8.3	$2''.0$	separate
$\Sigma 2807$	8.7, 8.8	$1''.9$	touching
$\Sigma 2509$	7.5, 8.3	$1''.7$	notched
$\Sigma 2843$	7.1, 7.4	$1''.5$	notched
$\Sigma 3062$	6.5, 7.4	$1''.5$	notched
$\Sigma 3017$	7.7, 8.6	$1''.4$	notched
$\beta 1154$	8.6, 8.8	$1''.2$	notched
$O\Sigma 50$	8.5, 8.6	$1''.1$	barely notched
$\Sigma 2054$	6.2, 7.2	$1''.0$	barely notched
$\Sigma 2438$	7.1, 7.4	$0''.8$	elongated
$\Sigma 2$	6.8, 6.9	$0''.7$	elongated

The telescope for this project is small but of high quality. The small aperture has helped reduce atmospheric effects. It is a 70 mm f/6.8 apochromat on a very sturdy mount and using powers of 137 and 200 each pair is examined for at least a minute. Even the closest pairs tend to 'jump' out in a few seconds but the extra time is useful for detecting doubles whose components have a large difference in brightness.

Some years ago, Peterson demonstrated for a 3-inch telescope working at x45, that such a telescope resolved stars independent of magnitude for secondaries brighter than magnitude 8 or so, fainter than that there appeared to be a linear relation between resolving power and the secondary brightness.

$$m = L - 2.4 + 1.6 log(D/S)$$

where m is the faintest companion likely to be seen, L is the limiting magnitude of the telescope, D is the separation of the pair in arc seconds and S is the limit of resolution on bright pairs for the eyepiece used. It would be interesting to see if this relationship works for different apertures.

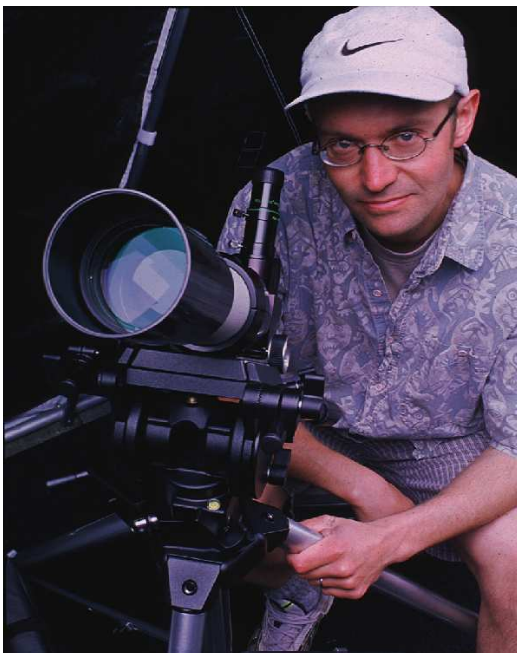

Fig. 10.5 Jerry Spevak and his 70mm apochromatic refractor

10.9 Seeing

An Airy disk surrounded by several stationary diffraction rings is, alas a rare telescopic sight - the presence of the Earth's atmosphere sees to that. In addition to absorbing the incident starlight, it also causes the star images to change in size (seeing), move about (wander) and to change in brightness (scintillation). Another significant effect which is better seen in larger telescopes at high magnification is the appearance of speckles which are diffraction limited images of the Airy disk and explained in more detail below.

Essentially, in a small telescope, aperture limits the resolution. With a large aperture the seeing limits the resolution.

Many observers try to quantify conditions of atmospheric steadiness and clarity by reference to a numerical scale. There are several scales of seeing and whether the numerical value of seeing increases as seeing gets better or decreases is purely a matter for personal choice. Aitken and van den Bos, for instance, both used a scale of 1 = worst to 5 = best with the occasional use of a + sign to indicate 'slightly better than' as in 2+.

It is difficult to justify a scale which goes from 1 to 10 for instance because it would be difficult to be that specific about what is, after all, a very subjective parameter.

The performance of a telescope on double stars can be improved by considering some of the following points:

- Don't take a telescope out of a warm house into a cold garden and expect to see point-like images straightaway. The telescope must be given time to reach the temperature of the night air. This goes for the eyepieces as well.
- Don't be put off by a little mist or haze or even thin cloud. The atmosphere on these occasions is usually calm and can result in good seeing.
- If housed in an observatory, open the dome as soon as is practicable. Just after sunset is not too soon. Keep the dome closed during the day but allow a little air circulation if possible.
- Don't observe from surfaces which absorb a lot of heat. Grass is more preferable to concrete.
- Don't use a magnification which is clearly too high for the state of the atmosphere. If the images do not show disks, wait until things have improved. If the star you are after cannot be resolved, switch to a backup programme of wider pairs but always be prepared to take advantage of good seeing when it occurs.
- Plan your observing so that your target stars are as close to the zenith as possible when you observe them.

Chapter 11
Reflecting telescopes and double star astronomy

Christopher Taylor

11.1 Reflectors versus refractors, optical principles

Even a cursory reading of the literature of visual double star astronomy is sufficient to show that the field has long been heavily dominated by the refractor, which remains the instrument of choice for many visual observers. It is not, indeed, hard to find statements backed by the highest authority alleging that for this type of observation a reflector must be of substantially larger aperture to match the performance of a refractor of given size[1]. There is, however, no basis whatever in optical theory for such claims nor, as will shortly be seen, do actual results at the eyepiece sustain this perception of the reflecting telescope as second-class citizen. This chapter will demonstrate that, and how, a reflector of good optical quality, maintained in proper adjustment, can be fully the equal aperture-for-aperture of the best refractor, matching the latter's resolution to the uttermost limits of visual double star astronomy, at least on fairly equal pairs. It is not amiss to recall at this point that the study of binary stars was founded by Herschel with reflecting telescopes and that its current limits have largely been set by recent observations with reflecting systems, both in terrestrial speckle interferometry and in the *Hipparcos* orbital observatory.

Present purposes would not be served by entering into the minutiae of the apparently interminable debate over the relative merits of the two classes of instrument, but there are important differences between their respective imaging properties, and handling characteristics in real observing conditions, which must be recognised by any observer who aims to push telescopic performance to its limits. There are, accordingly, a few fundamental optical principles which must be borne in mind as the essential context for what is said later in this chapter specifically about reflecting telescopes. In particular, given the myths, misconceptions and dubious anecdotal evidence common in the 'Refractor versus Reflector' debate, it seems appropriate to begin by stating clearly what are not the reasons for significant differences between the two types - not, at least, so far as double stars are concerned.

[1] For instance, van den Bos stated that a reflector must have a linear aperture 50% greater than that of an equivalent refractor.

One such notion holds that residual chromatic aberration is a serious limitation to the defining power of refractors with simple doublet O.G.s, and that the reflector therefore has a marked superiority in this sense. That there is, in fact, no theoretical justification for this view in the case of any refractor of sufficiently long focus to be used for high resolution imaging (say *f*/10, at least, for smaller apertures rising to *f*/18 or so for large instruments) has been known at least since the work of Conrady (1) . It was shown there that moderate levels of defocussing such as may be induced by secondary spectrum in such a refractor, that is up to one quarter or even one half of a wavelength phase-lag, does not significantly alter the diameter of the Airy disk formed by the telescope, despite its intensity declining noticeably. Effectively, the chromatic dispersion of focus is lost within the depth of focus naturally allowed by the wave theory; this is the reason why image definition is so good in refractors despite secondary spectrum. The result is that resolution on high-contrast targets such as double stars is fully maintained, even if some low-contrast fine detail may be lost in planetary images. That this conclusion is fully borne out by practical experience is convincingly demonstrated by the magnificent achievements in high-resolution double star astronomy of the best visual observers using the big refractors: one only need think of the Lick 36 -inch regularly reaching $0''.1$. in the hands of Burnham, Aitken and Hussey. Indeed, one of the greatest of recent observers of visual binaries, Paul Couteau, seems from the remarks in his well-known book (2) to consider the secondary spectrum of refractors to be a positive advantage. Clearly, three colour or apochromatic correction, whatever its benefits for the use of relatively short focus instruments in planetary imaging, is for the double star observer an expensive and dispensable luxury - the classical long focus doublet O.G. is more than equal to the task required.

The effects of central obstructions, often alleged to degrade imaging quality of reflectors quite seriously compared with that of refractors, can similarly be dismissed. By blocking a small central patch of the incident wavefront, the secondary mirror of a reflector removes a minor portion of the light from that process of mutual interference at focus, which otherwise produces a standard Airy diffraction pattern. The result is that an equal amount of light which would previously have interfered, constructively or destructively, with this obstructed portion in the process of image formation must now be redistributed in the Airy pattern. It follows on simple grounds of energy conservation that the amount and location of this redistribution of light in the image is essentially identical with the intensity distribution in the image which would be formed alone by just the light that has actually been blocked - a statement familiar to all students of diffraction theory as Babinet's principle (the Complementary Apertures theorem)(3). One can immediately see from this that, for the fairly small central obstructions of most reflectors, the amount of light redistributed in the image must be very small and, as the point-spread function of the obstructed central zone is very much wider than that of the full aperture (in inverse ratio to their diameters), this small amount of light is deflected from the Airy disk into the surrounding rings. It is, therefore, quite impossible for a secondary mirror blocking, say 5% of the incident light, to cause a redistribution of 20% of what remains from diffraction disk to rings, a change which would itself be near the limits of visual perception even on planetary images. This is the case of a ‘22.4% central obstruction’ in the linear measure usually applied to discussions of this issue, and even this is decidedly on the large side for most Newtonians, at least, of *f/6* and longer.

Central obstructions are not in fact the only possible cause of excess brightness in the diffraction rings nor, probably, indeed, the most important single cause in the vast majority of reflecting telescopes. The effect of deviation of light from the Airy disk into the rings is quantified by the Strehl ratio, a parameter commonly used as a measure of imaging quality and as a basis of optical tolerance criteria, which is the peak central intensity of the diffraction pattern actually formed by an instrument, expressed as a fraction of that of the ideal Airy pattern appropriate to the case. The essential point here is that any small deformations, W, of the wavefront converging to focus, whether arising in the telescope from surface errors of the optics or from aberrations, will reduce the Strehl ratio and so cause the kind of effect commonly attributed to ’central obstructions’. According to Maréchal’s theorem, this deviation of light from disk to rings is proportional to the statistical variance (mean square) of the wavefront deformations, W, thus:

$$Strehlratio = 1 - \frac{4\pi^2}{\lambda^2}.varW$$

This approximation holds for W values up to about the Rayleigh ‘quarter wave’ tolerance limit and in that range is independent of the nature of the wavefront deformations. More than half a century after Maréchal’s discovery it is extraordinary how little known this fundamental result(4) appears to remain in the practical world of telescope users and makers.

In particular, it turns out that spherical aberration (S.A.) in small doses mimics the diffraction effects of central obstructions particularly closely, putting extra light into the rings, while leaving the size of the Airy disk unaltered. With S.A. just at the Rayleigh limit, Maréchal’s theorem shows that the Strehl ratio will already have dropped to 0.8, an effect fully as large as that of a 30% central obstruction. The conclusion is that, unless a reflector is of very high optical quality and very precisely corrected, or has an exceptionally large secondary mirror (or both) any effect of the central obstruction will be swamped by that of S.A., to say nothing of other aberrations and optical errors. This is particularly significant in view of the prevalence of residual S.A. in reflecting telescopes: plate glass mirrors tend to go overcorrected in typical night time falling temperatures, so older optics even from professional makers are often undercorrected, deliberately; the absence of a simple null test for paraboloids, and the acquired skill necessary to interpret accurately the results of the Foucault test at centre of curvature, mean that amateur made mirrors are often only very approximately corrected; and Cassegrain systems, such as the ubiquitous SCT compacts, which focus by moving one of the main optical elements, necessarily introduce correction errors for all settings except that in which the principal focus of the primary mirror coincides exactly with the conjugate focus of the secondary. There is a very interesting field survey of the effects of residual correction errors on performance of reflectors (5). A further point here is that S.A.

is proportional to (aperture)^2 / focal length, so the claim that the 'cleaning up' of the image in a typical reflector by use of an off-axis unobstructed aperture proves that the secondary mirror is responsible for the less-than-ideal image at full aperture is obviously a misinterpretation of the evidence: simply by stopping down, both S.A. and 'seeing' effects are drastically reduced, naturally giving rise to the observed changes in image quality.

These conclusions are entirely vindicated by practical experience. In the 12-inch (0.32 m) *f*/7 Newtonian with whose star images this author has been intimately familiar since the 1960's, increase of the normal 16% central obstruction to 32% has no perceptible effect on the diffraction image of a first magnitude star, although the brightening of the rings has become very obvious at 60% obstruction. Again, a deliberate trial of this question was made by side-by-side star tests, on the same bright star, of a 4-inch refractor and a 6-inch Newtonian having 37% central obstruction. With both instruments showing a beautifully defined Airy pattern at x200, the greater relative intensity of the rings in the reflector was so small as to be barely detectable even after many rapidly alternated comparisons. It should be noted that even this rather large obstruction only stops about 1/7 of the incident light.

In short, the unavoidable presence of a central obstruction in most reflectors does not limit their resolution, or make it inferior to that of refractors of equal aperture. On the contrary, by stopping out the centre of the mirror, the mean separation of the points on the incident wavefront is increased, thereby decreasing the size of the Airy disk which arises from their mutual interference, so the resolving power of a reflector on fairly equal double stars is actually greater than that of a refractor of the same aperture, other things being equal. In truth, this last effect is almost negligible for central obstruction much below 50% but it may surprise some readers to learn that for the highest resolution on equal pairs this author deliberately stops out the central 72% of the telescope's aperture[2] - a 9-inch central obstruction on a 12-inch reflector! Of course, such doubles are extreme high contrast targets and therefore react quite differently to such treatment, compared with planets or even unequal double stars, whose resolution would be seriously impaired by this tactic.

To bring this discussion to its conclusion, the real differences between refractors and reflectors which are important for high-resolution imaging of double stars are very simple and very fundamental: refractors refract, while reflectors reflect and refractors do this at four (or more) curved optical surfaces as against only one in a Newtonian. These two facts are so obvious that they are often ignored but they are, far more than any other factors, truly the crux of the matter in comparing the optical performance of the two main classes of instrument.

That image-formation is, in the one case, by refraction, and, in the other, by reflection has radical implications for the relative immunity of the refractor from image degradation due to surface errors of the optics, whether arising from inaccuracy of figuring, thermal expansion or mechanical flexure. Thinking in wave terms, one can say that the function of a telescope's optics in forming a good image of a distant star is simply to cause rays from all points of the plane wavefront incident on

[2] None of the double star results given later were dependent on this trick however

the aperture to travel exactly the same number of wavelengths (optical path-length) in arriving at the focus, so that they may interfere constructively there and form a bright point of light. That is all there is to image formation in the wave theory, whether by refraction or reflection (and this is precisely why results like the Airy pattern and Maréchal's theorem arise) - arrival in phase of all rays at focus. The refractor achieves the necessary phase delay of the near-axial rays, relative to the peripheral rays which must follow a longer route to focus, by intercepting them with a greater thickness of dense optical medium to equalise axial and peripheral optical path lengths. That is to say, the telescope uses a convex lens. The reflector attains exactly the same result by bouncing the axial rays back up to focus from further down the tube than the peripheral rays, that is, it uses a concave mirror.

It immediately follows that this differential phase-delay, and hence quality of image, is dependent on thickness of the O.G. at any point relative to that at its edge, in a refractor, but on actual longitudinal position of the mirror surface relative to the edge, in a reflector. Further, errors of glass thickness in the first case only cause optical path length errors (μ - 1) times, or approximately half, as great while errors of surface in the second case are doubled on the reflected wavefront, as such errors are added to both the to and fro path length. Consequently, to achieve any particular level of wavefront accuracy var (W), and thus image quality (cf. Maréchal's Theorem, above) in a reflector requires optical work roughly four times more accurate than in the case of a refractor and, for exactly the same reason, the latter is about four times less sensitive, optically, to uneven thermal expansion of its objective. Lastly, because mechanical flexure does not alter thickness of an O.G. in first approximation, while it has an immediate and direct effect on local position of surface elements of a mirror, refractors are hugely more resistant to the optical effects of flexure (6,7) .

That refractors share the work of focussing light between at least four curved surfaces, compared to only one in a Newtonian, is equally fundamental and takes us to something which will be the central theme of the next few pages: optical aberrations and their avoidance or management. The requirement that a curved mirror surface return all rays incident parallel to the optical axis to focus with equal optical path lengths, so forming a fully corrected image there - as discussed above - is alone sufficient to determine uniquely the form of that surface. A very simple geometrical construction shows that the mirror must be a paraboloid of revolution. In other words, the requirement that axial aberrations, specifically S.A., be zero defines the optical configuration uniquely and leaves no adjustable parameters free for reducing or eliminating off-axis aberrations (apart, trivially, from the focal length). The result is that all reflectors, Newtonian, Herschelian, or prime focus, having only one curved optical surface, necessarily suffer from both coma and astigmatism. Unless other adjustable optical surfaces are introduced into the system, nothing can be done to mitigate the full force of these off-axis aberrations and, as will be seen in the next section, coma severely limits the usable field of view of all paraboloid reflectors and makes them hypersensitive to misalignment of the optics (collimation errors). A refractor objective, by contrast, possesses at least four independently adjustable curvatures and opticians have known since the time of Fraunhofer how to use this

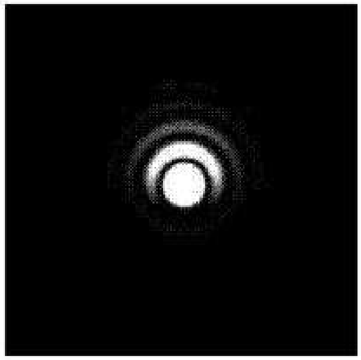

Fig. 11.1 A quarter wave of coma

freedom to eliminate both the axial aberrations and coma, in the so-called aplanatic objective[3]. Most quality refractor O.G.s are nearly or quite aplanatic, leaving only astigmatism as the factor limiting field of view, a very much less serious constraint which leaves most refractors with a far larger field of critical definition and far less sensitivity to collimation errors than all Newtonians, at least. Compound reflectors such as Cassegrains or catadioptrics represent a halfway stage in this sense between Newtonians and aplanatic refractors but most of these pay the price of decreased (rarely eliminated) coma in increased trouble from S.A. Coma arising from miscollimation in reflectors is perhaps the most obnoxious of all aberrations to the double star observer, as it rapidly destroys the symmetry and definition of the star image: even wave of coma, that is just at the Rayleigh tolerance, is quite sufficient to make the diffraction rings contract into short, bright arcs all on one side, an image distortion quite unacceptable for critical double star observation - see Fig. 11.1 (8).

What all of this amounts to in practice is that a reasonably well-made Fraunhofer achromat is a hugely more robust instrument than a typical reflector in the face of the thermal variations, mechanical flexure and shifting collimation which commonly arise in real observing conditions, and so can be relied upon far more than the comparatively delicate, fickle reflector to deliver critical definition at a moment's notice with minimal cosseting and adjustment. It is also more likely to meet the optical tolerances necessary for such diffraction-limited performance. These are the reasons why the refractor has so often been the first choice for observers of close visual binaries.

[3] The need for multiple-surface adjustability to minimize aberrations is, of course, the reason why all short-focus wide-field imaging units such as camera lenses and wide-field eyepieces must have four or more components.

However, as will be seen shortly, none of this implies an inevitable inferiority of the reflector in this field of astronomy, for good optics and proper management of the instrument will easily hold in check all those adverse factors to which the reflector is more sensitive, to an extent quite sufficient to deliver star images equal to any seen in a refractor[4] All the supposed optical defects of the reflector are removable or fictitious and, of course, a good 0.3-m reflecting telescope is a far less expensive item than an equally good 0.3-m refractor! For reaching the observational limits, however, the unrelenting emphasis must be on quality optics and their proper management, in particular to maintain accurate collimation so that all high power images may be examined truly on axis, free of the dreaded coma. This is the subject of the next few sections. What follows is largely based on experience with a Newtonian reflector, with which this author has done most of his double star astronomy, but results comparable with those reported here are probably within reach of good longish-focus reflectors of virtually any type, given the same aperture.

11.2 Coma and astigmatism

For a paraboloid mirror, the angular expansion of an image due to coma, ξ, depends on the telescope diameter D and focal length f by the following relation:

$$\xi = \frac{3}{4}(\frac{D}{2f})^2 tan\theta$$

where θ is the angle of the incident ray to the optical axis. The angular expansion of the image due to astigmatism is:

$$\sigma = (\frac{D}{2f})tan^2\theta$$

For the case near the optical axis tan $\theta \sim \theta$ in radians and so in this case these relationships simplify to:

$$\xi = \frac{3\theta}{16F^2} \quad and \quad \sigma = \frac{\theta^2}{2F}$$

where F = f/D is the focal ratio.

It is more convenient in practical terms to express the angular distance off-axis in arcminutes and the aberrations in arcseconds, when the first result becomes

$$\xi = \frac{11.25\theta'}{F^2}$$

[4] With the possible exception of some enhancement of the diffraction rings in reflectors exhibiting resuidual S. A. If this is the only fault, the telescope will perform just as well on double stars but faint companions may be swamped. For this reason, a good refractor will often outperform a reflector on contrasted pairs even when the two instruments are absolutely matched on equal doubles.

This is in close agreement with Bell (9) . Since ξ is linear in θ, whilst σ is quadratic, it follows that, on moving off-axis, coma is always the first aberration to appear and that, for the small θ values with which we are concerned, astigmatism is generally negligible compared with coma for all except very extreme focal ratios. Their ratio is $\sigma/\xi = 8F\theta/3$ which, for example, only reaches unity at f/6 rather more than 3.5 degrees off-axis and is $\leq$ 0.1 at this f ratio out to θ = 21.5 arcmins. A Newtonian showing astigmatic star images is, therefore, either grossly misaligned - to the point that the reflection of the diagonal in the main mirror will be wildly eccentric - or has a badly distorted optical figure.

11.3 Impairment of resolution/image quality.

Bell (ref. cit, page 95) says that resolution will be noticeably impaired if the off-axis aberrations (which the image may exhibit even at the centre of the field due to imperfect collimation) are approximately equal to the empirical resolution limit $4''.56$/D (Dawes limit). Despite some statements to the contrary in the literature (e.g. Sidgwick 1979, p.51.) there is no doubt whatever that this criterion is true, as is fully borne out in my experience by a good deal of very exacting double star observation at the 0.3 - 0.4 arcsecond level with an f/7 mirror of 12-inches diameter. Thus to achieve full resolution we must operate on or near the true optical axis, at

$$\theta \leq \theta_{max}$$

where θ_{max} is the angular displacement off-axis at which ξ + σ = the Dawes limit . In view of the comments above regarding the smallness of σ, we can approximate this condition closely by the simpler ξ = Dawes limit (first order approximation, valid for all normal f ratios) which, with all angles in radians, is

$$\frac{3\theta}{16F^2} = \frac{2.21 \times 10^{-5}}{D}$$

where D is the aperture in inches.

Hence

$$\theta_{max} = \frac{1.18 \times 10^{-4} F^2}{D}$$

or in arcminutes:

$$\theta_{max} = \frac{0.405F^2}{D}$$

This angle is the limitation to field of critical definition centred on the optical axis and is, therefore, also a measure of the maximum angular error which can be tolerated in collimation of the telescope's optics;specifically, in the squaring-on of the main mirror. The noteworthy point here is the extremely small value of this angle even for unfashionably long Newtonians (which, of course, are far better in this sense (since

$$\theta_{max} \propto F^2$$

), far smaller in fact than the attainable tolerance of the methods of collimation in general use: for the 12-inch at f/7.04, the formula gives θ_{max} = 1.6 arc minutes - a value again fully borne out by my observational experience[5]. In fact, I would say that for really critical double star work right at the limit of resolution on a Class I or II (Antoniadi) night, aberrations become quite noticeable even at half this level, so reducing θ_{max} to 0.8 arcmins i.e. 48 arcseconds - about the size of Jupiter's disk! Furthermore, as this angle varies as the square of the f-ratio, the modern generation of short-focus Newtonians are at a huge disadvantage here and it is probably true that no Newtonian at f/5 or below will ever, in real observing conditions, reach anything approaching its limiting resolution. Even if one can guarantee the hyperfine collimation tolerance demanded (and in my experience these instruments are used most of the time with squaring-on checked only to $\pm 0.5^\circ$or worse, i.e. only the first approximation to collimation is carried out), the objects observed will almost never lie in this minute axial patch of the field of view.

Under what conditions will the first order approximation above for θ_{max} be valid? We may reasonably say that astigmatism is negligible if, say, $\sigma/\xi \leq 0.1$ and this imposes the condition that

$$F\theta_{max} \leq 3/80$$

which on substituting the first order approximation for θ_{max} (in radians) yields

$$1.18x10^{-4}F3/D \leq 3/80$$

. Thus the mathematics is self-consistent, and the first order result for θ_{max} is valid, if and only if F3 / D $<$ 318. For the 12.5-inch telescope this parameter has the value F3 / D = 27.9 - well within t he 'coma-dominated' regime. In fact, there is no focal ratio of Newtonian likely to be encountered in ordinary astronomical use, in which the off-axis limitation to field of critical definition is due to anything other than the onset of essentially pure coma.

It is worth bearing in mind a few numerical values of this field, $2\theta_{max}$, as given by equation 11.3 for some common Newtonian configurations: 8.6 arcmin. for a 6-inch at f/8; 3.6 arcmin. for an 8-inch at f/6; 2.0 arcmin. for a 10-inch at f/5. Equation 11.2 then implies that at the edge of a field n times wider than this, the aberration will be n times larger than the Dawes limit.

11.4 Practical and observational consequences.

Of prime concern here is not the issue of obtaining the largest possible field of view from the telescope at full resolution, since wide-field observation is, almost by

[5] This implies a maximum field of critical definition of 3.2 arcmin., compared with an actual field of 2.4 arcmin. on this instrument at the power used for subarcsecond pairs (x825)

definition, not high resolution imaging. In any case, most of us have to make do with the fixed F and D of the telescope we have and are, therefore, stuck with the fixed θ_{max} value those imply. The real issue for practical observing, if the telescope is to be used as a serious optical instrument and not merely as a crude ’light bucket’, is that of sufficiently accurate collimation of the optics to guarantee maximum image-quality and full, unimpaired resolution somewhere (preferably the centre!) in the field of an eyepiece of sufficient power to reveal that resolution to the eye. If, through failure of collimation, the optical axis of the primary mirror falls outside such a field by more than θ_{max} , the telescope will never reach its limiting resolution however good the ’seeing’ may be and even this is a hopelessly sloppy criterion since it allows nothing for the aberrations of the eyepiece when used far off-axis. The matter is certainly not trivial as typical fields of these very high power eyepieces are only of the same order of magnitude as ?max itself.

The usual collimation procedure (10) of looking into the telescope in daylight through an axial pinhole and centering/ rendering concentric the reflections of the main spec in the diagonal and of diagonal in main spec will, if carried through carefully, bring the optical axis into coincidence with the centre of the eyepiece field to within a tolerance of order 10 arcminutes. At this point, the telescope, if of good quality, will very likely yield quite pretty and satisfying images even of planets at moderately high powers (approx 20 per inch of aperture) and stars will appear round or pointlike up to about these magnifications; it will not, however, reach the limiting resolution for that aperture, falling short of this by a factor of 2 or more in all probability. This is well illustrated by a typical experience with the author’s 12.5-inch. After full collimation on 1996.80, the telescope completely split and separated γ^2 Andromedae (O 38) at x825 in good but not perfect seeing, when the pair was at 0.50 arcsec. A few nights later, after a hurried setting-up in which it had not been possible to complete the final stages of collimation, there was no trace of the companion visible at that power in the same instrument, despite superlative seeing and the star on the meridian. The residual aberrations which blotted out the little star on this occasion were nevertheless still so small as to be completely inappreciable in planetary images; Saturn that night was magnificent at x352.

To go beyond this sort of 30 - 50% performance there are two further stages which must be completed, what one might call ’fine collimation’ and ’hyperfine’, the first a refinement of the usual daylight procedure, the second using night-time star tests. No progress can be made on either of these unless the telescope is fitted with fine adjustment screws controlling the squaring-on of the main mirror cell, which are themselves driven by controls within comfortable reach of the eyepiece. N. B. it is vital that the observer is able to alter the attitude of the main mirror at will while looking through the eyepiece. Given how very simple it is to contrive this on the majority of Newtonians, it is remarkable how few instruments, commercial or home-made, are fitted with the necessary gear. Having equipped the telescope with this, one can proceed with daylight fine collimation. Mark the centre of the main mirror surface (pole of the paraboloid) with a round spot at least 1/8 inch across - Tippex is very suitable - the precise size is of no importance but what is absolutely vital is that it be plainly visible from the eyepiece drawtube, be exactly concentric with the pole of the mirror and be fairly accurately circular. Point the telescope at the daylit sky and look along the axis of the drawtube, accurately defined by a 'dummy' eyepiece or high power eyepiece from which the lenses have been removed. Having made the usual adjustments to the diagonal, use the mirror-tilt fine adjust screws to move the reflection of the diagonal in the main spec until its centre falls exactly on that of the Tippex pole-mark. This should be done by winding the adjust screws, and hence the reflection of the diagonal, to and fro repeatedly while watching through the drawtube, until absolutely satisfied of complete concentricity of diagonal-reflection and pole-mark - so far as the eye can judge. This will probably have taken collimation to within 2 or 3 arcminutes of target. All of this assumes the mounting of the diagonal to be rigid, without perceptible play; the small shifts in position (e.g. rotation about the optical axis) of a floppy diagonal can easily introduce randomly changing collimation errors of 10 arcmins or more, so defeating all one's best efforts. Nor can it be assumed that collimation is an infrequent necessity, let alone a once-for-all ritual; even a permanently mounted instrument is subject to frequent shifts and distortions (mechanical flexure, thermal expansion and contraction etc.) at the arcminute level and my personal experience is that serious attempts on subarcsecond double stars require re-collimation at each observing session. However, once in the habit of it, the process takes only a couple of minutes - hardly a major chore.

For the final, hyperfine stage one has to wait for a class I or II (Antoniadi) night, to push the telescope to its absolute limits. This stage is, of course, only relevant to observing on such nights, in any case. Charge the telescope with a power of x50 to x80 per inch of aperture (e.g. 1/4 inch eyepiece and Barlow pushed well in) and focus on a second or third magnitude star. An immediate test of the quality of the telescope is that even at this power the star should come crisply to focus so that the central disk is almost pinprick-like (this may well be surrounded by a fainter and much larger fuzzle of instrumental and atmospheric origin but ignore that to start with) and unless the instrument is of uncommonly long f-ratio there will be virtually no depth of focus - the tiniest displacement of the eyepiece in or out will noticeably de-focus the star image[6]

It is, however, the diffraction rings which are far the most sensitive indicators of image degradation due to atmosphere, bad optics or imperfect collimation , which is why one so rarely sees the ideal Airy pattern of the books under real 'field' conditions - and which, rather than the central disk, are therefore used for monitoring hyperfine collimation. The rings are, in particular, extremely sensitive to coma due to miscollimation and will show a very pronounced lopsidedness at a far lower level of maladjustment than is needed to make the central disk go visibly out of round. The result in a Newtonian can be a really quite serious loss of resolution as all the light previously distributed evenly and symmetrically around the rings is dumped into a collection of much brighter short arcs all to one side, creating a sort of false image several times the size of the Airy disk. It seems that this degree of comatic

[6] The theoretical depth of focus is $\pm 8F^2\Delta\lambda$ where $\Delta\lambda$ is the maximum tolerable wavefront deformation arising from malfocus (1). If we adopt the Rayleigh tolerance limit $\Delta\lambda = \lambda/4$, this becomes $\pm 2F^2$ (e.g. $\pm 99\lambda$ at f/7, which is just over 0.05 mm.)

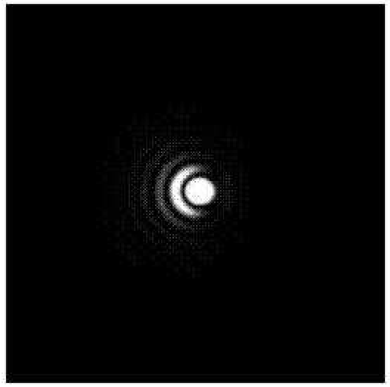

Fig. 2

Fig. 11.2 The effect of slight miscollimnation in a reflector

distortion occurs at about the 2 - 3 arcminute level of collimation error one can hope to achieve at the fine collimation stage - depending, of course, on f-ratio but that is my experience at f/7.

Assuming that fine collimation has been carried out with sufficient care and that the optics are of reasonable quality, a close look at the halo or fuzzle surrounding the main star image should reveal that it is at least partly composed of very roughly concentric bright arcs vaguely centred on the star disk. In a Newtonian of typical proportions there are likely to be 3 or 4, quite bright (often a lot brighter than the theoretical Airy ring pattern, as noted in section 1) and you will be doing extremely well at this stage to see them as arcs of more than about 120 degrees. Unless the night is a true class I (i.e. very rarely at most sites) the rings are not easily seen on full aperture the first time one tries this; they will be fragmented, distorted crinkly-wise and constantly on the jitter. If previous adjustments have brought the telescope within 2 or 3 arcminutes of true, you will be operating by now well within the coma-dominated regime discussed earlier and an idealised version of what you will see (ignoring atmospheric interference) is thus:

What you almost certainly will not see is a complete set of circular rings.

Coma in a Newtonian off-axis is external; that is to say the light of the diffraction rings is displaced to the side furthest away from the optical axis. The remedy to the state of affairs shown above - the final hyperfine collimation - is therefore simple (in principle!): while keeping close watch through the eyepiece, wind the fine-adjust controls on the main spec very slowly so as to displace the distorted image thus:

re-centering the star in the field as this adjustment proceeds. It may well be that the outer arcs will disappear during this process but the important thing is that the innermost arc should expand tangentially so as to encircle the central image as a complete ring of uniform brightness. If that state is achieved, you will be in the

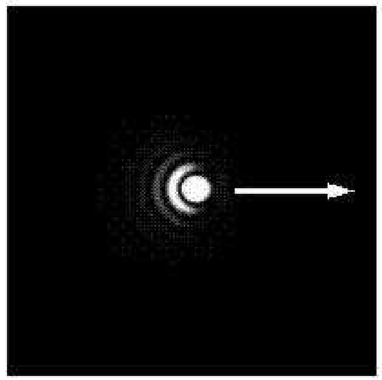

Fig. 3

Fig. 11.3 Correcting the miscollimnation

fortunate position of having a telescope which will reveal detail right down to its diffraction limit - atmosphere permitting!

It should now be evident why such insistent emphasis was placed earlier on the need for the collimation controls to be within comfortable reach of an observer actually looking through the instrument, for without such provision fine collimation will obviously be almost impossible and, in view of the very high powers needed during this stage, hyperfine collimation will be absolutely out of the question. This last stage of collimation, using the structure of star images, must be conducted with the telescope at full aperture but it may take some initial practice for less experienced observers to see the relevant details of the diffraction pattern. Readers unaccustomed to such high-power observation and to the appearance of the Airy rings may find it helpful to follow the suggestions made in section 6 below before attempting star tests and hyperfine adjustment.

11.5 On the possible occurrence of astigmatism in star tests.

The plain fact is that there shouldn't be any. Provided that the optics themselves are of true figure, coma is the only image defect which can occur for small deviations off-axis due to imperfect collimation of a Newtonian. By the time that even rough collimation has been done, the instrument should be well within the coma-dominated regime, as explained above. Conversely, to make astigmatism dominate, the telescope would have to be miscollimated by an angle of order $\theta = 3/8F$ which is huge compared with the alignment tolerances discussed above. At this point the image distortions due to off-centering would be huge themselves - stars would ap-

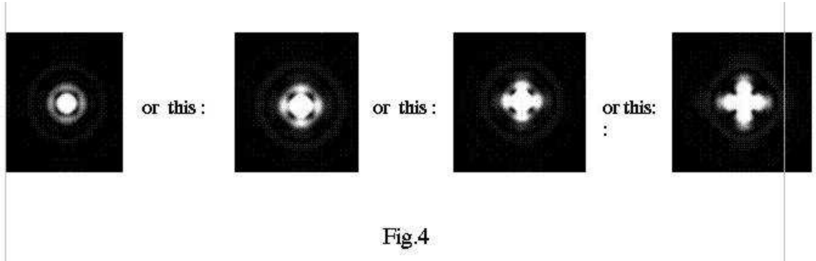

Fig. 11.4 Correcting the miscollimnation

pear all sorts of curious shapes even on the lowest powers and resolution would be degraded to tens of arcseconds - and the crudest of rough collimation by eye would eliminate the problem. In other words, *small image distortion in a Newtonian due to small errors of collimation is never astigmatism.*

If, nevertheless, the star image during hyperfine collimation looks fixedly like this

(in order of increasing badness) then you have got a small dose of astigmatism. As it can't be due to miscollimation, it must be due to distortion of figure in the optics but remember that there are four components to the optical train: main mirror, diagonal mirror, eyepiece and your eye. It should be quite easy to determine which of these is responsible for the problem, since all except the diagonal can be rotated about the optical axis without affecting the collimation: whichever rotating component carries the axis of symmetry of the cruciform image with it, is the villain of the piece and has a distorted astigmatic figure. If this does turn out to be the main spec, it is still not cause for despair since the condition may be temporary and remediable and, in any case, if it is only as 'bad' as the first diagram above it will have negligible effect on telescopic resolution and one can comfortably live with it, even if permanent i.e. the telescope is still a good one. It should be noted that the machine-generated images in Fig. 11.4 are something of a theoretical ideal, as they have been computed only for exact paraxial focus. In reality, astigmatism is more likely to be noticed as a distinct elongation of the star disk when slightly out of focus, this elongation reversing on passing through the focal point. This is the most characteristic symptom of astigmatism and is very pronounced even in the first case depicted above, in which the focal star disk remains virtually unaffected.

Temporary astigmatic distortion of the main mirror can be due to a variety of causes but principally three: uneven thermal expansion/contraction in changing temperatures, pinching or stressing of the disk due to overtight clamping or fit in the mirror cell and flexure of an inadequately supported disk under its own weight. Thermal effects can easily, and frequently do, bring about a miraculous transformation of a very good mirror into one for which there are no words in polite society; unfortunately it never works this alchemy in reverse! If afflicted with this malady, there is nothing for it but to pack up for the time being while thermal relaxation takes its course or, perhaps, to pass the time with some undemanding low-power sightseeing.

One can, however, take common-sense precautions to avoid those recipes which create the problem in the first place, the two worst and commonest being indoor storage at, say, 20 -25° C of an instrument that may be called into play at a moment's notice outdoors at 5° C or below, and inadequate ventilation and other provisions for temperature stabilisation in small observatories having full exposure to the noonday sun - heating one's telescope to perhaps 40° C is not a good preparative for high-class images a few hours later!

Mechanical distortion, whether due to pinching or to lack of adequate support of the disk, is essentially a question of mirror-cell design and management, which are dealt with extensively in the large literature of telescope making. There are two basic principles which cannot be overemphasised. Firstly, positive clamping of a mirror in its cell will almost always impair good figure and should be avoided. Secondly, gravitational flexure of a disk of thickness T scales as D^4/T^2, so increasing rapidly with aperture D even for a constant thickness-to-diameter ratio (T/D). The immediate consequence of this last point is that the requirements for adequate mirror-support grow rapidly with size of disk from 3-point support which may suffice for full-thickness mirrors up to 10 or even 12 inches diameter, to 18 or 27-point which is necessary for virtually all mirrors of 20 inches and above. The current fashion for lightweight, thin paraboloids is very much more demanding in this respect and it is unlikely, for instance, that a 10-inch of 1 inch thickness will attain the levels of performance referred to here if carried on anything less than a 9-point support system.

Such optical woes are emphasised in this chapter because reflectors are very much more vulnerable to these conditions than refractors, as noted earlier. The conclusion does not follow, however, that Newtonians are inferior to refractors in all the most challenging fields of double star observation. On the contrary, all the causes of temporary distortion or misalignment of mirrors are avoidable and a good Newtonian well managed will reach the Dawes limit just as well as any refractor.

11.6 How to see the diffraction limit of any telescope.

” Seeing is in some respect an art, which must be learnt.” William Herschel 1782

The Airy diffraction-pattern is not easy to observe astronomically in its full and perfect glory - practically, never in anything other than a small telescope (less than about 5 or 6 inches in aperture, the comments below referring primarily to larger instruments) under virtually perfect seeing conditions. Otherwise the best one can hope for is a partial, flickering view which it may take long experience as a telescope user to recognise as ‘diffraction’ rather than seeing blur: it took this author over 20 years with the same 12.5-inch mirror. The rings, in particular, are incredibly sensitive to atmospheric distortion, incomparably more so than the diffraction disk itself, and simply vanish without legible trace in Newtonians of typical amateur size, the moment the seeing falls below I or II (Ant.). It is therefore of great value to have

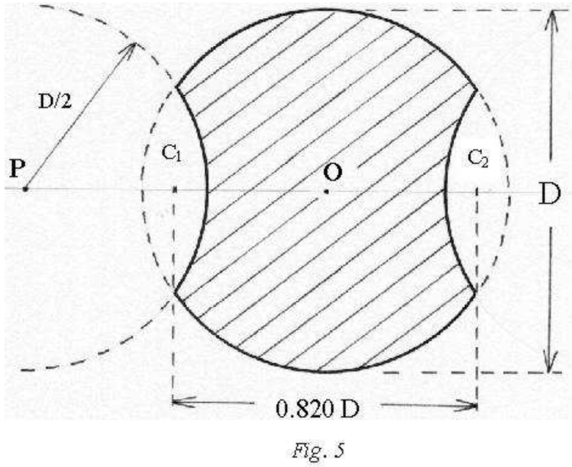

Fig. 11.5 The Rayleigh limit aperture mask

a means of displaying these and related effects at the level of the telescope's limiting resolution much more clearly, and so to train the eye to see structure at this level.

The first stage is to learn just what the resolution limit of one's telescope actually looks like, just how tiny this really is, how very much smaller than the usual star-image as seen on 90% of nights. It is very easy to go on using a telescope for years, especially if only using powers up to 20 or 25 per inch of aperture, firmly under the impression that the 'splodge' one sees a star as at best focus on typical nights is the diffraction disk and that, even if not, there will be no finer level of structure visible in the image. This is wrong even as a rough approximation, but may be a difficult lesson to unlearn and require a change of observing habits. The agitated 'fried egg' which one sees in apertures over 6 inches on all except the very finest nights is nothing whatever to do with the true diffraction image, either as to size or structure. Nevertheless, on all except the worst nights, the true limiting-resolution star disk is visible, buried in the heart of the obvious image, quite accessible (at least in 'flashes') to a trained and sufficiently agile eye, perhaps a factor of five smaller than the 'splodge'. However, no amount of general stargazing will bring about this training of the eye, for which specific exercises are required.

A great aid to this first step of adjusting the eye to the scale of the true diffraction image is a simple aperture-mask of this form:

cut from a sheet of any stiff, opaque material and placed over the aperture (diameter D) of the telescope. Each of the segments symmetrically cut out of the mask is bounded by a circular arc of diameter D struck from a centre P where OP = 0.820 D. A fabrication accuracy of $\pm$ 1/16 inch is perfectly adequate.

With this applied to the telescope, one has a Michelson stellar interferometer specifically designed to produce interference fringes having a spacing exactly equal to the Rayleigh diffraction limit $1.22\lambda/D$ for that telescope. Observe a first magnitude star (not a close double!) with this at a power of at least 40 per inch of aperture

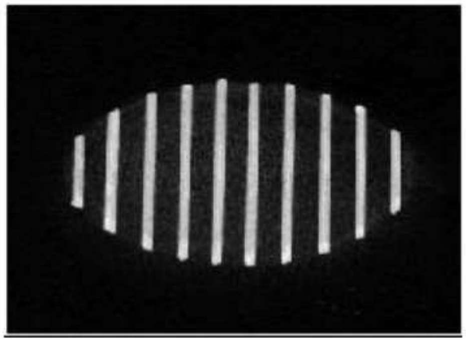

Fig. 6

Fig. 11.6 The spacing of these fringes equals the resolution limit of the telescope at full aperture, according to the Rayleigh criterion

(40D), focussing carefully. This time, it is not necessary to wait for a night of first-class seeing, as the interference fringes ‘punch through the seeing’ to an extraordinary degree, a surprising and rather curious fact commented on by many users of the interferometer since Michelson himself in 1891. What you will see is an enlarged and elongated diffraction disk divided into extremely fine bright fringes, perhaps as many as 10 or 11 in all, thus:

Unless you have done something like this before, you will probably be surprised at how small this scale of image structure is - in all probability a lot smaller than the star images usually seen in the same telescope. The magnification required to separate these fringes clearly will depend on your visual acuity and this observation provides an interesting opportunity to test the question of so-called ‘resolving magnification’. The majority of observers will almost certainly find that the commonly alleged figure of 13D to 15D is hopelessly inadequate and some may need 50D or more.

Having accustomed the eye to the appropriate scale of image structure, the next stage is to become thoroughly familiar with the Airy diffraction pattern itself. This is made much easier if the pattern is enlarged relative to the scale of the seeing by use of a series of circular aperture stops reducing the telescope’s entry pupil to D/4, D/2, and 3D/4. It is advisable when doing this with any reflector having a central obstruction to make both the D/4 and D/2 stops off-axis in order to keep vignetting by that obstruction to a minimum. On a night of seeing I or II (Ant) focus the telescope on a 2nd or 3rd magnitude star with a power of at least 50 D (The author’s standard working power for this type of observation is 66 D = x825) and keep this same magnification on throughout, while examining the image successively with apertures of D/4, D/2, 3D/4 and D. If the telescope is of good quality and properly collimated, you should have no difficulty at all in seeing a nearly perfect ‘text book’ Airy pattern with the smallest stop: a big, round central disk (not in the least point-like at this power of 200 or more per inch of aperture used), sharply defined, and surrounded by several concentric diffraction rings, extremely fine even on this power, nicely circular and separated by perfectly dark sky.

On running successively through the larger apertures D/2, 3D/4 and D this Airy pattern will shrink dramatically and, unless the seeing and the collimation of the telescope are perfect, it will also suffer a progressive deterioration. The result on full aperture is unlikely to bear much resemblance to the ideal image shown by D/4, even ignoring the difference of scale, partly due to the much greater sensitivity of the larger aperture to atmospherics and ’seeing’, and partly to the almost inevitable residual coma arising from incomplete collimation. Note that equation 11.1 implies that coma at full aperture D will be 16 times that at D/4 for the same offset θ, so that an asymmetry like that shown in Figure 11.2, or worse, will now make its appearance even where none was visible at D/4. Nevertheless, if the night is sufficiently fine, it should be possible with persistence to recognise some trace of the pattern of disk and rings even on full aperture. Now is the moment to return to the business of ’hyperfine’ collimation discussed earlier, completion of which should result in a perfectly round Airy disk, at least, even though the rings at full aperture are unlikely ever to be as clean as those seen at D/4. The telescope will resolve to the Dawes limit if and only if this state is achieved; if the Airy disk absolutely refuses to come round as a button the instrument is defective and consideration will need to be given to the possible causes of image distortion discussed in section 5 or, in worst case scenario, to the imperfections of the main mirror itself.

The final stage of this ocular training programme is to learn to cope with the seeing on more typical nights when the diffraction rings will be so fragmented and perpetually on the jitter as to be completely unrecognisable. Here I refer to seeing down to about III (Ant.), the worst at which high- resolution astronomy is possible. But it is not in the end the rings with which we are primarily concerned and the emphasis on them here has been purely for their great sensitivity as a diagnostic tool, for identifying and curing removable coma in the telescope. The real image is the disk and the fundamental point about that is that it is often still there even on second-rate nights when the outer envelope of the seeing blur may reach several times Dawes limit. Though then quite invisible to an observer not specifically trained to work at the diffraction limit, the Airy disk will time and again reveal itself to a trained eye as an intense nucleus buried in the heart of that seeing blur. The object of the exercises suggested in this section is that it should now be possible, with some further practice on these more typical nights, to do what the untrained eye never could - to pick out the true disk and ignore the atmospheric ’noise’.

This last stage is perhaps the most difficult, though it should not present great problems if the earlier exercises have been successfully completed, and the requirement now is practice on nights of less than perfect seeing: practice, practice, and more practice. In fact these ocular gymnastics soon become quite easy and instinctive. It is probably in part the lack of such training and consequent failure to distinguish the seeing blur (the gross image outline) from the still visible Airy nucleus which is responsible for the persistent myth that seeing limits ground-level resolution to 1 arcsecond at best, and is certainly the origin of some of the more spectacularly absurd figures one sees quoted for alleged image size. This author's experience of typical conditions at a very typical lowland site may be of some interest in this context: using a 12.5-inch Newtonian at 400 feet elevation (130 m.) in central England, an equal $0''.75$ arcsecond pair (such as η CrB in May 2000) is steadily separated by a clear space of dark sky at x238 in seeing of only III - II (Ant.), while p.a. measures of pairs at 1.8 arcsec and below are frequently within 2° or so of subsequently verified definitive values even when the seeing is III (e.g. 138 Psc. Jan. 2000 and ξ UMa. April 2000, both at x238). These observations prove that the mean angular size even of the gross outline of the image as seen under such very middling conditions is no more than about 0.6 arcsec, in the centre of which the smaller Airy nucleus is still fitfully visible. When the seeing improves to I or II this accuracy of p.a. measures extends down to pairs at 1 arcsec or even slightly below, and this is using the most primitive of home-made micrometers on an undriven altazimuth telescope.

When described minutely like this, the business of fine-tuning the capabilities of instrument and observer is perhaps likely to appear a rather arduous road. In fact, this could scarcely be further from the truth, as the training of the eye is essentially once-and-for-all, while one soon drops into a virtually unconscious habit of the collimation procedures described earlier, which then take merely a few minutes at the start of each observing session. While it must be emphasised in the strongest terms that, as Herschel put it, “you must not expect to *see at sight*”, there is no obvious reason why a new observer, starting from scratch and following the programme outlined in this section, should have any difficulty in attaining a fully trained eye within a few months of commencing observations. I believe the value of the approach outlined in this section lies entirely in making that possible - it is certainly not necessary for the process to take the twenty years it took this author (with the same telescope) in the absence of any such detailed guidance!

11.7 Achievable results.

So, what sort of performance and results can one expect from a fairly typical amateur reflecting telescope, say of 6-12 inches or so aperture and of good optical quality? Without the small investment of trouble in adjustment of the instrument and training of the eye outlined in the preceding paragraphs, the field of wide doubles is open to the observer, that is to say pairs from 1-2 arcsec upwards. Diffraction-limited performance will not be attained by a substantial margin and such an observer will probably consider resolution of a 1 arcsecond pair something of a triumph, while subarcsecond doubles remain an unattainable holy grail. Much rewarding observation can be done in this rather undemanding way but that ingredient which gives double star astronomy its deepest fascination will be largely lacking: motion. Very few of these wider pairs have orbital periods of less than centuries so the observer limited to this type of observation is largely condemned to studying binaries as static showpieces, missing out thereby on the grandest gravitational ballet in the whole of celestial dynamics. Adding the dimension of time, and being able to watch these majestic systems actually in action, adds incomparably to the interest of the observations.

The representative selection of this author's observations quoted below illustrate what can be done with very ordinary amateur equipment in this dynamic, subarcsecond domain, given the attention to preliminaries described above. The instrument used is the 12-inch (0.32-m.) Newtonian referred to earlier and shown in Figs. 11.7 and 11.8. It has a plate glass primary mirror figured by George Calver in 1908 which, as discussed in section 1, was deliberately left undercorrected by its maker, with the residual spherical aberration consequently tending to give rise to diffraction rings of largely enhanced intensity. While as pointed out earlier the effect of this is to make such a reflector no match for a good refractor on very unequal pairs below about 1.5 arcsec, the spurious disk remains at the ideal Airy size or even slightly smaller, so equal (?m 1) close pairs can be resolved at least as well as in a refractor of the same aperture. Accordingly, the results quoted are all for binaries whose components do not differ by much more than 1 magnitude in light.

Lest the reader imagines that successful observation of subarcsecond binaries requires an expensive professionally-constructed instrument equipped with the latest hi-tech. conveniences, or that the author has enjoyed such advantages in making the observations reported here, a brief description of the 12-inch will serve as a useful counterexample. The telescope was entirely amateur built some sixty years ago and, although standing about 9 feet (2.7 m.) tall, has never been housed in any form of building or weatherproof cover. One result of this is that while the mechanical structure of the instrument stands permanently on a concrete foundation at a good observing site in the author's garden, the entire optical system must be stored indoors and mounted anew in its various cells, etc, at the beginning of each observing session. This, of course, means that full collimation of the system is an unavoidable necessity every time it is used - the telescope simply would not work otherwise. Thanks to intelligent design, however, this entire optical assembly and collimation routine only takes five minutes or so each evening: on the general view, Fig. 11.7 note (a) that all optics are mounted externally, and very easily accessible, on the 'tube' which in reality is nothing more than a box-girder for rigidity (b) the linkage rods running from the inner corners of the fully adjustable main mirror cell, up the length of the tube, to the eyepiece assembly at the top; these terminate in the collimation control knobs which can be seen at the lower corners of the eyepiece turret housing in Fig. 11.8 and make fine adjustment of squaring-on of the main mirror while simultaneously looking through the eyepiece or drawtube a very quick and painless affair.

The instrument weighs about 1500 pounds (680 kilograms) and is an altazimuth, lacking not only (therefore) setting circles or clock drive but even any form of manual slow-motion controls. It is true that the 12-inch moves very smoothly on its bearings and is extremely stable but it remains something of an acquired skill to

Fig. 11.7 The 12.5-inch reflector (Peter Seiden)

follow the diurnal motion at high power simply by pulling directly on a handle at the top of the tube, to say nothing of taking p.a. measures of close double stars! The full force of this remark will perhaps be appreciated when it is borne in mind that an equatorial star takes rather less than ten seconds to cross the full field of view at the power most commonly used for ‘subarcseconders’, and that the observer, perched precariously on a step-ladder some considerable height above the ground, must perform this manual tracking continuously, co-ordinating hand and eye to a precision of a few tens of arcseconds, at the same time leaving the mind free to concentrate on what is seen in the eyepiece. This is observing in the classic style of William Herschel, far removed from the digital conveniences of the twenty-first century.

This telescope has a primary focal ratio of 7.04, with a central obstruction equal to 16.3% of the aperture diameter. Optical quality is such that the author’s standard working power for all subarcsecond double stars is x825, at which single stars appear ’round as a button’ whenever the seeing is II-III (Ant.) or better, and the instrument would comfortably bear magnifications even higher were it then possible

Fig. 11.8 Eyepiece end of the 12.5-inch (Christopher Taylor

to manage its altazimuth motions sufficiently well. It is clear from the observations that the smallest double star separation detectable with the 12-inch (see below) is, even so, limited by magnification, not by definition and image quality. Statistical analysis of accumulated observations of equal bright pairs at 0.4 - 0.9 arcsec shows that the apparent star-disk diameter of a 5th or 6th magnitude star at x825 in good seeing is 0.311 ± 0.037 arcsec; this observed size of spurious disk is only 37% of that of the full theoretical Airy disk (out to first zero) and agrees exactly, after scaling for aperture, with the result independently determined for a 4-inch (0.102 m) refractor also used for double star observation. This last comparison shows that the image definition of a Newtonian can be not only as good as that of a refractor of the same aperture but, after scaling, can match that of a far smaller refractor - a much more severe test. It must be emphasised once again, however, that such quality of imaging can only be expected of a Newtonian even at this f-ratio after full and accurate collimation, as detailed earlier.

The double star results actually achieved with this 12.5-inch Newtonian are best represented by the following tabulation of the typical appearance at x825 of bright, approximately equal pairs at successively smaller separations, in seeing II-III (Ant.) or better. Listed here are only those categories of target which can in any sense be considered seriously testing of the telescope's capabilities, all wider pairs always appearing on any good night as two well-separated stars divided by a large space of completely dark sky: -

There is no doubt that such performance claims run heavily counter to the perceptions of the large majority of telescope users who are, perhaps, too undemanding of their instruments. To any reader inclined to be sceptical of the above results I would point out that the author had been using this same telescope on double stars and other 'high resolution' targets for more than twenty-five years before the ob-

Table 11.1 Summary of observations near the limit of resolution

Separation ($''$)	Typical appearance of star disks
0.4 - 0.5 or so	Two completely separate disks parted by small gap, persistently split in good seeing e.g. λ Cas. 1995.03 ($0''.43$), ϕ And. 1995.80 ($0''.48$) β Del. 1998.72 ($0''.50$), ω Leo 1996.26 ($0''.52$), 72 Peg. 1994.08 ($0''.53$)
0.35 - 0.36	Two distinct disks in contact (tangent),occasionally just separating in good seeing e.g. β Del. 1996.87 ($0''.35$- 6)
0.33 - 0.34	Disks now slightly overlapping,giving"figure 8", heavily notched but *not* separating, e.g. δ Equ. 1995.79 ($0''.33$-4), α Com. 1996.46 ($0''.33$)
0.29 - 0.32	Very elongated single image ("rod"), occasionally just notched at best moments; an easy elongater, the disk elongation quite obvious in even moderate seeing, e.g. δ Ori. Aa (Hei 42) 1998.11 ($0''.31$).
0.24 - 0.28	A single oval disk ('olive'), the elongation still quite pronounced although still noticeably less than in the last case, no hint of a notch now e.g. β Del. 1995.85 ($0''.28$), α Comae 1997.35 ($0''.26$), A 1377 Dra. 1997.80 ($0''.25$), γ Per (WRH 29 Aa) 1996.88 - 1997.19 ($0''.24$)
0.21 - 0.23	Slightly oval disk, elongation small but still quite sufficient to read p.a. Confidently at best moments; now becoming noticeably more difficult, the difference between $0''.21$ and $0''.24$, very obvious to the eye, e.g. κ Peg. 1996.88 ($0''.21$)
0.17 - 0.20	Very slightly oval disk, the elongation very small but in the best seeing absolutely definite, especially by comparison with neighbouring single star as a 'control; now becoming difficult to estimate p.a. confidently, detection of elongation nearing the limit for x825 e.g. ζ Sge. (AGC 11) 1996.77 ($0''.19$) which was appreciably easier than α Com. 1998.41 ($0''.175$) the current limit for positive detection of a double star with the 12.5-inch at this power.
Somewhere at,	Beyond the limit for reliable detection at x825, the star disk *not* clearly
or above 0.13	distinct from that of a neighbouring single star even in very good seeing κ UMa. (A 1585) 2000.23 ($0''.13$)

servations themselves forced the possibility of such subarcsecond performance on the attention of a mind not predisposed to expect it; further that all such double star observations are made essentially 'blind', the observer having no prior information on 'expected' p.a., and only a rough figure for separation, on going to the eyepiece. So the relentless internal consistency of the observations with respect to separation, and their close individual agreement in virtually all cases with definitive values of p.a. subsequently consulted as an objective verification, are more than sufficient to establish the objective validity of these results. In the entire set of observations of pairs below 0.5 arcsec there are only two or three cases of clear contradiction with this post-observational check, none of which were in good seeing. These very few failures are, moreover, offset by a number of other instances of apparent contradiction where more authoritative data subsequently obtained have proven that the observations were correct and that it was the published information available at the time which was in error, this having occurred for λ Cas., α Com., γ Per., δ Ori. Aa and κ UMa.

Such results should really occasion no surprise as they are actually in precise agreement with Dawes' limit (0.365 arcsec here) as can be seen from the first three classes in the tabulation, as well as agreeing pretty closely with what would be expected from the previously quoted size of star disk determined quite independently from observations of much wider pairs. All of this is, in fact, entirely in line with the mainstream of historical experience in this field, from Herschel who founded subarcsecond double star astronomy in the early 1780's with a 6.2-inch mirror (0.157-m.), right down to the Hipparcos satellite observatory which made accurate measures of pairs down at least to 0.13 arcsec in the early 1990's with a 0.29 m. mirror - rather smaller than that used by the author, although admittedly having the huge advantage of perfect seeing! The limit on detectable separation, for instance, in the tabulation above, at 0.48 of Dawes' limit, is closely comparable with the average for the closest class of new discoveries made by S. W. Burnham with 6-inch aperture i.e. 0.53 x Dawes.

The author's observations therefore establish conclusively that double star elongation of reasonably equal pairs is reliably detectable in a 12-inch mirror at x825 down to a limit somewhere about 0.17 arcsec, as with α Com. in May 1998. All such pairs down to 0.24 arcsec inclusive are easy elongaters in good seeing, only the last two classes in the tabulation really presenting any significant difficulty under the best conditions. What is perhaps most remarkable about such observations is the extraordinary sensitivity of the shape of blended or partially resolved double star images to really minute changes in separation: in the 12-inch at x825, a change of only 20-30 milliarcsecond (mas) is quite appreciable to the eye in pairs from 0.4 arcsec downwards, while an increase of 60-80 mas is sufficient to transform the appearance of a pair totally, from 'olive' to 'disks tangent', as in the case of β Delphini 1995-1996. It is amazing but true that a ground-based amateur telescope of unremarkable aperture and positively primitive lack of sophistication, used visually in the time-honoured fashion, can and does reveal clearly angular displacements smaller than any detail actually resolved by the Hubble Space Telescope.

Access to this subarcsecond domain opens the door on a dynamic world of binary star astronomy usually considered the exclusive preserve of the professional using powerful instruments equipped with the latest technology and sophisticated methods such as speckle interferometry. Indeed, several of the pairs mentioned above have been used in recent years as test objects for evaluating the performance of adaptive optics systems on professional telescopes of 1.5-m. aperture and above, while the entries in the 3rd CHARA catalogue show that all are favourite targets of the speckle interferometrists. It is one of the better-kept secrets of observational astronomy that it is nonetheless perfectly possible, with care and determination, to follow many of these systems' orbital motion visually with an amateur telescope of only slightly larger than average aperture - which means, almost necessarily, a reflector. This should not be a surprise to anyone: almost all of these binaries were, in fact, discovered in just this fashion, using very much this range of apertures, by e.g. Struve II with the Pulkova 15-inch, Burnham with 6 and 9.4-inch instruments, etc.

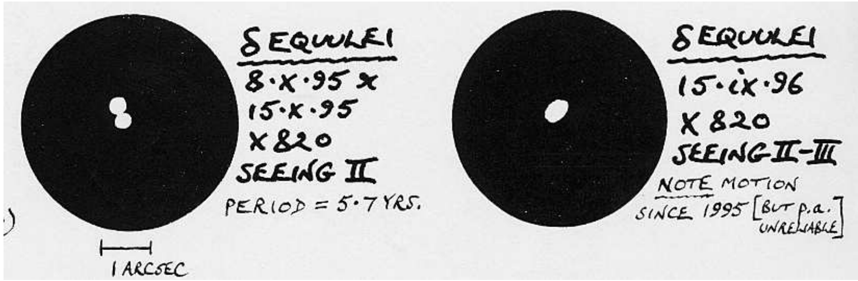

Fig. 11.9 Observations of the pair δ Equ with the 12.5-inch reflector

Among the author's more memorable experiences with the 12.5-inch telescope are several concerning some of the most legendary of the short period visual binaries. δ Equ. ($O\Sigma$535), perhaps the most famous of all such systems, was long the holder of the record for the shortest period of all visual binaries, at 5.7 years. This pair is actually quite easy on a good night in the 12.5-inch when at its widest as in 1995, appearing then as an absolutely unambiguous figure 8, only just failing to separate completely. The orbital motion is phenomenally rapid, a total transformation in the appearance of the star occurring in a twelvemonth or less, as the author witnessed in 1995 and 1996 - see Fig. 11.9. This motion is actually so rapid that, if caught in very good seeing at the critical moment in the orbit, a change plainly perceptible at the eyepiece of the 12.5-inch will occur in only seven or eight weeks, δ Equ. having crossed an entire class in the tabulation of appearances given earlier.

β Del. (β151, period 26.7 years) is another pair whose orbital advance in a single year is plainly visible in the 12-inch reflector even without quantitative measurement, its steady year-by-year opening out and rotation in p.a. having been conspicuous in that telescope in the years 1995-1998. This was first noted on 13th Nov. 1996, the entry for which in the author's obs. book reads 'β Delphini x820 showing an immediately obvious 'rod' / 'figure 8'; on further scrutiny, several times glimpsed two distinct stars just touching i.e. this pair now much easier than a year ago? ... p.a. constantly and easily legible at 330° -335° ". (This was a rough 'by eye' estimate only, not a measurement, but very noticeably larger than it had been twelve months earlier), the seeing only fair at III-II. The definitive position at the time of this observation was subsequently found to be (0.35-0.36 arcsec, 323). See Fig. 11.10.

Other similar cases have been α Com. (Σ1728, period 25.9 years) and γ Per. (WRH 29 Aa, period 14.7 years) a beautiful system which is the brightest visual binary in the heavens which is also an eclipsing variable(11). The double star observations of γ Per. have been mostly by speckle interferometry on 3 to 4-metre class telescopes, and κ Peg. (β989, period 11.6 years). The 12-inch followed the inward march of Σ1728 over the late 1990's, beginning with 'figure 8' at 0.33 arcsec in 1996, all the way down to 'elongation v. slight but perfectly definite' at 0.175 arcsec in 1998, the smallest separation so far detected with this telescope. The annual change in this star was quite apparent at each of these three observing seasons and, although it was much more difficult in 1998 than it had been a year earlier at 0.26

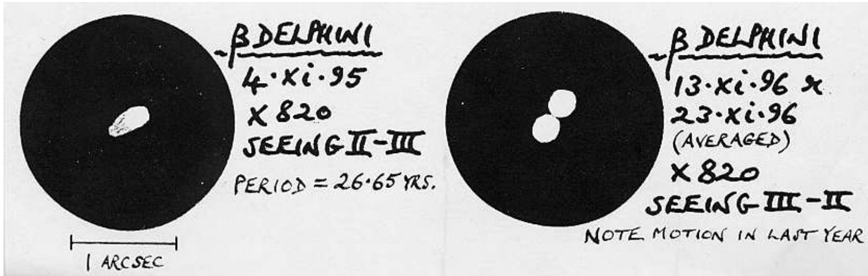

Fig. 11.10 Observations of the pair β Del with the 12.5-inch reflector

arcsec, even the limiting elongation to which it was followed was quite unmistakeable - 'like a dumpy egg' - by repeated comparison with the absolutely round disk of Arcturus, then at the same zenith distance. (Given that 0.33-0.34 arcsec appears as 'figure 8', this is in fact exactly what one should expect of the same pair at 0.175 arcsec, as can easily be seen from scale drawings of spurious disks overlapping to the appropriate degrees).

11.8 Some advice

If such are the results achievable with the decidedly primitive amateur-built telescope described earlier, it must follow that similar performance is within reach of virtually any Newtonian having a good mirror at f/5 - 6 or longer, adequately supported on a mounting of sufficient stability and rigidity. Those further refinements which the author's instrument so conspicuously lacks - permanently mounted optics of modern low-expansion glass in a telescope having a clock drive or at least good manual slow motions - will, of course, make this easier but are not indispensable. The real essentials for such subarcsecond performance are listed here, together with some general points of advice on the conduct of this type of double star observation:

1. While any good instrument is worth giving a fair trial on subarcseconders, it is unlikely, in the case of reflectors especially, that a system having a primary f-ratio less than 5 will achieve the level of performance described above, even if claimed to be 'diffraction limited' (a decidedly loose phrase): equation (11.3) makes it clear that collimation tolerances for critical imaging quality become almost impossibly tight at F/5, in addition to which these deeper curves of the main mirror are more difficult for the optician to control by most of the methods of figuring and testing still in use, so that such 'fast' paraboloids are rarely as good as the best of longer focus. In general it is clear for reflectors that the longer the focus the better, within reason; even F =12 or 15 would certainly not be excessive here.
2. It goes without saying that such extremes of imaging performance can only be expected of good optics, of course, but it would be a mistake to suppose that the

author's 12-inch is wildly exceptional in this respect. Calver was undoubtedly a master optician but he was working with both materials and methods which made his job decidedly more difficult than that of his modern successor; there must be many more recent mirrors in amateur hands which are just as good as this 1908 glass. It is probably true that any paraboloid as good as, or perhaps a little better than, the Rayleigh quarter-wave criterion will deliver the sort of results described here, if well managed and satisfying the other necessary conditions. Remember, however, that the Rayleigh criterion means that the extreme distortion peak-to-valley of the wavefront must not exceed one quarter of the relevant wavelength of light used; a phrase such as 'a one-tenth wave mirror' may, in extremis (and often does!), mean that the mean deviation of the glass from perfect figure does not exceed one tenth of a test wavelength (usually He - Ne laser at 6328Å) which is itself considerably larger than the 5100 - 5300Åvalue relevant to visual observation. In such terms, a surface only just satisfying the Rayleigh criterion would be described as 'one-thirteenth wave', so beware ambiguous descriptions of optical quality from telescope retailers, manufacturers and others!

3. On the needlessly controversial subject of magnification, the only rule is that there are no rules, and any attempt to set hard and fast limits to what may be used on a given aperture is merely an arbitrary and unhelpful constraint hampering the realisation of the telescope's uttermost capabilities. The wise observer will give full play to the instrument's whole range of powers without prejudice and finally settle on that magnification which best reveals the details sought, irrespective of whether that also yields the crispest, aesthetically most satisfying image. The last is a merely cosmetic consideration. As to high, or even very high, powers - say from 40 per aperture-inch upwards - be neither obsessed with, nor afraid of them. It should be pointed out that the 'resolving magnification' is the theoretical minimum for visibility of small detail, not a maximum; oft-repeated attempts to set this as an upper limit to useful magnification, taking 1 arcminute as the smallest detail resolvable by the eye and Dawes' or Rayleigh's limits as the smallest that one may be attempting to see with the telescope, are fallacious on all counts: visual acuity varies hugely from one individual to another but the typical night-time resolution of a normal eye is 2.5 to 3 arcmins., not 1, while the tabulation earlier of subarcsecond double star appearances shows that we may very well be in quest of detail as small as 0.5 Dawes' limit, to magnify which up to comfortable visibility therefore requires a power of at least 65 per aperture-inch, a figure itself not in any sense an upper limit. This is quite in line not only with the author's experience with 12-inch spec. (x65.8 per inch) and Jerry Spevak's with 70-mm O.G. (x72.4 per inch, see Chapter 10) but also that of most observers of such close visual pairs. You may be able to reach these subarcsecond limits at substantially lower magnifications but I shall be surprised!
4. A vital corollary of the last point is that the whole mechanical construction of the telescope must be such that both its rigidity and smoothness of movement are able to handle the high magnifications necessary. This is a rather demanding requirement, which in larger apertures is virtually certain to be incompatible with the lightweight construction favoured for portable telescopes, many of which

are hugely under-engineered in this respect. For a reflector over about 6 inches aperture, a permanently mounted instrument is certainly better than a portable for this class of observing and it is evident from this consideration and point (i) that the popular f/4.5 Dobsonian of large aperture is just about the worst possible choice here. Such telescopes are not the tools of high-resolution astronomy.

5. Full and thorough collimation of a reflector's optics as frequently as may be needed to maintain their precise alignment is an absolute essential, as discussed earlier in sections 3 and 4. Equation (11.2) now makes it very obvious that the smallest errors of squaring-on at the arcminute level will be quite sufficient for coma to swamp many of the finer features in the tabulation of star disk appearances given in the last section.
6. The quality of the seeing is of vital importance. Don't waste time attempting to observe subarcseconders when the Airy disks of these stars are not visible (say, seeing III Ant. or worse).
7. These pairs should only be observed when at a large elevation above the horizon, preferably within about 1 hour of meridian passage, and certainly not when below about 35°. Below 40°elevation, elongation of star disks due to atmospheric spectrum becomes increasingly evident and the seeing steadily deteriorates due to the lengthening visual ray within the turbulent atmosphere. Resist the temptation to try for subarcseconders which never rise above these elevations in your sky - the results will only be gibberish.
8. This sort of observing does not require phenomenal eyesight; the author is slightly short-sighted and certainly of only average visual acuity even when corrected for myopia. What it does emphatically require is a mental receptiveness to every nuance of what is seen, a power of concentration which devours to the last drop what the eye has to offer. This ability to use one's eyes takes training and practice, of which something has already been said in section 6. It is remarkable how widely telescope users differ in this respect, even among active observers, but fancy equipment is no substitute here for essential observing skills. In training the eye to this activity it makes obvious sense not to be too ambitious at first but to start with pairs at several times Dawes limit and then work steadily downwards. The furthest fringes of subarcsecond double star observing are undoubtedly an extreme sport, a sort of 'athletics for the eyes', which demands fitness as with any such activity. Illness, tiredness or significant alcohol intake are all quite incompatible with peak performance, which depends as much on the observer as it does on the instrument.

   Spectacle wearers must, necessarily, abandon their glasses for this work, as the high magnifications used require eyepieces whose eye-relief is much too small to accommodate them. This is no problem whatever to those suffering only from pure long- or short-sight as simple re-focus of the telescope takes care of all, but astigmatism is a more serious matter. Uncorrected, this will cause spurious elongation of star disks with obviously undesirable consequences, so the astigmatic observer who would pursue this game must resort either to contact lenses or to a tight-fitting eyepiece cap carrying the appropriate corrective glass (e.g. old spectacle lens or piece cut centrally from one).

9. Unequal close pairs are much more difficult than equal pairs at the same separation, especially in reflectors generating accentuated diffraction rings, in which an inequality of even 1 magnitude may cause considerable difficulty in the clear sighting of a companion anywhere near the first ring and a magnitude disparity of 2 or only a little more makes it practically invisible. Most of the remarks above concern approximately equal pairs (magnitude difference less than 1, say) and it makes sense to begin with these on first setting out to crack subarcseconders. An illustrative example here is Albireo, the bright component of which is itself a very close double (MCA55) having a brightness inequality of about 2 magnitudes: at 0.38 arcsec this is very much more difficult in the author's 12-inch (e.g. obs. 1996.80) than an equal pair such as δ Equ. at 0.33 arcsec, probably, in fact, as difficult as any pair successfully observed with that telescope. The effects of seeing and of use of different optical systems on the detectability of these unequal pairs is altogether a more complex affair than the corresponding questions for equal doubles and their observation consequently yields much less reproducible results.
10. For all really doubtful or difficult cases, Herschel's advice could not be bettered: while leaving the eyepiece and focus untouched alternate in quick succession between views of the target double and of a nearby single star at about the same altitude, so using the roundness of the latter as a 'control' or comparison for the observed disk shape of the double. If the comparison star shows any significant elongation, the entire observation should be rejected.
11. Lastly, we come to perhaps the most important point of all for any observations which may with any justification be challenged or doubted, in which category should probably be included all alleged sightings of pairs equal or unequal, separated by less than twice the Dawes limit for the instrument used. As a matter of elementary scientific method it is essential that the observer has some independent means of checking each observation and so proving its validity to the sceptic (quite possibly the observer themselves). This requires that the observation is always made 'blind' with respect to some observable parameter of the pair, the observer having deliberately gone to the eyepiece not knowing everything about the current appearance of the target, so that the only possible source of knowledge of the parameter is the observation itself. The observed value can then, post-obs., be checked against the 'correct' or expected value as an objective criterion of verification (O.C.V.). The most obvious choice of O.C.V. is the position angle. Thus, and only thus, can observer prejudice, the phenomenon common in some less rigorous visual astronomy of 'seeing what you expect to see', be eliminated and these extremes of double star observation be securely founded on objective detection of the chosen targets[7] If in any doubt about p.a. at the first observation of a difficult pair where the seeing is less than ideal, do not check the value then

[7] This is flatly contrary to the (bad) advice given in some handbooks but it must be recognized that questionable observations made in the absence of any O. C. V., or where none is possible (e.g. as in claims to have seen the central star of the Ring Nebula M57 with small telescopes), are quite meaningless.

but re-observe the target on better nights until confident of the result, and only then consult the O.C.V.

12. To conclude, enough has surely now been said to make a powerful case for the reflecting telescope as fully the equal of the refractor, aperture for aperture, in at least some of the most demanding classes of double star observation. The author hopes that this may be an encouragement to users of good reflectors to venture into a deeply fascinating field of observation from which the speculum has too often been unjustifiably excluded by false preconceptions of the superiority of the lens.

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Chapter 12
Simple techniques of measurement

Tom Teague

12.1 Background

It is not necessary to possess expensive or advanced apparatus in order to begin making accurate measures of double stars. This chapter discusses three different techniques, in ascending order of sophistication: the ring method, the chronometric method, and finally the use of reticle eyepieces. Of these, the ring method is the simplest, requiring in its crudest form nothing more than an ordinary stopwatch with lap facility. By the addition of a crosswire and position angle dial, the observer can begin to measure closer pairs. Even an illuminated reticle eyepiece requires no great financial outlay, and permits observations comparable in accuracy with those achieved using a filar micrometer.

12.2 The ring micrometer

Invented by the Croatian Jesuit astronomer Roger Boscovich (1711-87), this is an elegant method of measuring differences in right ascension and declination. In its true form, the ring micrometer comprises a flat opaque ring mounted at the focus of the telescope objective. Using a stopwatch, the observer times transits of double stars across the ring. The times at which the components cross the inner and outer peripheries of the ring, together with the declination of the primary component and the known value in arc seconds of the ring diameter, contain all the information necessary to calculate the rectangular coordinates of the pair (i.e. the differences in right ascension and declination separating the two stars), from which it is then possible to derive its polar coordinates (ρ, θ).

It cannot be denied that the mathematical process of reducing the results is somewhat cumbersome, and must have been almost prohibitively tedious in the days of slide rules and logarithm tables, but the advent of modern electronics has banished such difficulties forever. The observer who makes good use of a computer or programmable calculator need not be deterred by the mathematical complexities which are, in any case, more apparent than real.

Commercially made ring micrometers are no longer obtainable, and the construction of a good one is not for the faint-hearted. My own, manufactured by Carl Zeiss Jena, consists of a metal ring mounted on a centrally perforated glass diaphragm which is fitted at the focus of a positive eyepiece. Happily for those who prefer not to undertake their own precision engineering, it is not actually necessary to have a purpose-made ring micrometer. All that is required is an eyepiece having minimal field curvature and an accurately circular field stop. It is the latter which serves as the micrometer. Some modern eyepieces, although of acceptable optical quality, have plastic field stops that may not be truly circular. Select a good quality eyepiece with a flat field and a metal field stop. It is possible to flatten the field by incorporating a Barlow lens into the optical train.

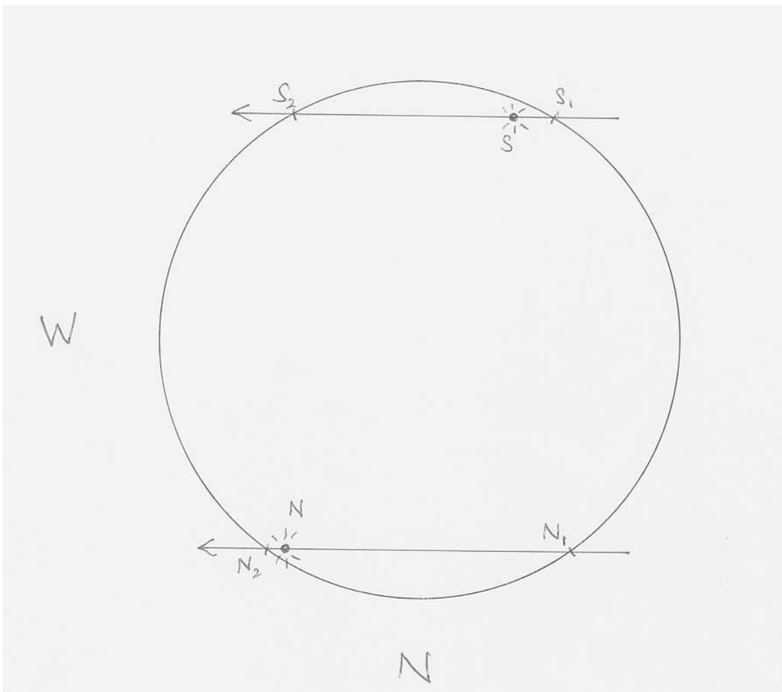


Fig. 12.1 Timing the transits of a wide pair of stars to determine the accurate diameter of a field stop or ring.

The first step is to calibrate the eyepiece by determining the radius of its field in arc seconds. A simple method of doing this is to time how many seconds of mean solar time it takes a star of declination δ to drift across the field diametrically, multiplying the result by 7.5205 *cos* δ. Even the mean of a number of such timings, however, is unlikely to be very accurate, since the observer has no way of being sure that the star has passed through the exact centre of the field of view, as opposed to trailing a chord.

A more reliable calibration method is to use a pair of stars having declinations which have been determined to a high degree of precision. The Tycho-2 catalogue will yield plenty of suitable candidates. In order to minimise the effects of timing errors, choose stars of relatively high declination, between 60 and 75 degrees north or south of the celestial equator. The difference in declination of the two stars should be slightly less than the diameter of the field stop or ring. Their separation in right ascension is less important, but should obviously not be inconveniently large.

The two stars are allowed to drift across the field, so that one star, N, describes a chord near the north edge of the field and the other, S, near the south edge. The times at which each star enters and leaves the field are recorded using a stopwatch (Fig. 12.1). A cheap electronic sports watch with lap counter will be found perfectly adequate.

Two angles, X and Y, are required in order to calculate the precise radius of the field stop in arc seconds. Suppose that star S, of known declination δ_N, enters and leaves the field at N_1 and N_2 respectively, and star S, of declination δ_S, enters and leaves at S_1 and S_2. Let $\Delta\delta$ be the difference in declination between the two stars. Then:

$$tan\,X = \frac{7.5205(S_2 - S_1)cos\ \delta_S + 7.5205(N_2 - N_1)cos\ \delta_N}{\Delta\delta} \qquad 1$$

$$tan\,Y = \frac{7.5205(S_2 - S_1)cos\ \delta_S - 7.5205(N_2 - N_1)cos\ \delta_N}{\Delta\delta} \qquad 2$$

From which the radius of the field, R, may be derived as follows:

$$R = \frac{\Delta\delta}{2\ cos\ X\ cos\ Y} \qquad (3)$$

Take the mean of not fewer than 30 transits. For the greatest possible accuracy, allow for the effects of differential refraction (see Chapter 22).

The procedure for measuring a double star is as follows. Set and clamp the telescope just west of the pair to be measured, so that the object's diurnal motion will carry both components, A and B, across the ring as far as possible from its centre (Fig. 12.2); they should both transit the ring near the same (north or south) edge unless they are very widely separated in declination, in which case they may pass on opposite sides of the centre of the ring. The importance of ensuring that the stars pass close to the north or south edge is that it minimises the impact of timing errors upon $\Delta\delta$. However, it should not be carried to extremes, as the precise moment of ingress or egress of a star that merely grazes the field edge will eventually become impossible to pinpoint.

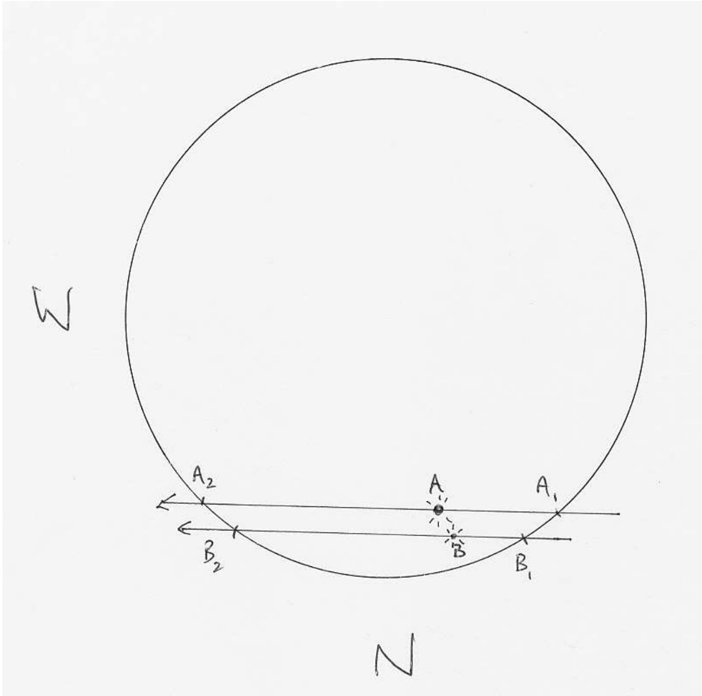


Fig. 12.2 Using the eyepiece field stop or ring to measure a pair of stars by transits.

The first transit should be used as a 'reconnaissance' to determine and record the sequence of appearances and disappearances. On subsequent transits, the observer uses a stopwatch to obtain the times (A1 , A2 , and B1 , B2) at which each star enters and leaves the field; these times are noted in tabular form, as shown in Table 12.1.

Table 12.1 A specimen observation of ΣI 57 made on 1997, October 27. The three transits are individually numbered in the top row of the table. Also recorded in each column is the portion of the field in which the transit took place (north or south, as the case may be)

	1 (N field)	2 (N field)		3 (S field)
A_1	0.00	0.00	B_1	0.00
B_1	29.36	30.95	A_1	3.56
B_2	276.77	270.68	A_2	251.80
A_2	279.81	275.06	B_2	281.69

In order to calculate the position angle, θ , and separation, ρ , of the pair, it is first necessary to determine the differences in right ascension, Δ_α , and declination,

Δ_δ, between the two components. The time at which each star transits the centre of the field is given by the mean of the times at which it enters and leaves. Hence the difference, $\Delta\alpha$, in RA between the two stars, A and B, is given by:

$$\Delta\alpha = \frac{(B_1 + B_2)}{2} - \frac{(A_1 + A_2)}{2} \qquad (4)$$

The result is expressed as a time difference. At a later stage, after we have ascertained the individual declinations of both components, we will be able to convert Δ_α into seconds of arc.

In order to obtain the difference in declination, Δ_δ, between the two stars, we first need to ascertain the distance, D, in declination between the centre of the field and each of the stars, A and B:

$$D_A = R\ cos\gamma_A \qquad (5)$$

$$D_B = R\ cos\gamma_B \qquad (6)$$

where the angles γ_A and γ_B are given by the following equations:

$$sin\gamma_A = \frac{7.5205\ cos\ \delta_A\ (A_2 - A_1)}{R} \qquad (7)$$

$$sin\gamma_B = \frac{7.5205\ cos\ \delta_B\ (B_2 - B_1)}{R} \qquad (8)$$

The difference in declination between the two objects is then given by:

$$\Delta\delta = D_A \pm D_B \qquad (9)$$

The value of D_B is added to D_A when the stars are on opposite sides of the centre of the field and subtracted from it when, as is more usual, they are on the same side. Note that in the latter case, the sign (positive or negative) of $\Delta\delta$ varies according to whether the north or south portion of the field is used. When both stars pass to the north of the field centre and Δ_δ is positive, B lies south of A; a negative result indicates the contrary. When both stars pass to the south of the field centre, the rule is reversed.

Since only the declination, δ_A, of the main component, A, is usually known in advance, the declination, δ_B , of the secondary component, B, must initially be given the same value for a first approximation. Once a preliminary value has been derived for $\Delta\delta$, the result is added to or subtracted from δ_A (as the case may be) to obtain a refined value for δ_B, from which $sin\gamma_B$ and thence Δ_δ may be recalculated.

We are now in a position to convert Δ_α into arc seconds. To do this, multiply by 15.0411 cos δ where δ is the mean declination of both stars.

Having thus obtained final values for Δ_α and Δ_δ, we use simple Pythagorean trigonometry to work out the polar coordinates, ρ and θ and

$$\rho = \sqrt{(\Delta\alpha)^2 + (\Delta\delta)^2} \qquad (10)$$

$$\theta = tan^{-1}(\frac{\Delta\alpha}{\Delta\delta}) \qquad (11)$$

When calculating θ, it is necessary to allow for the quadrant in which the companion (B) star lies by applying the appropriate correction, as shown in Table 12.2.

Table 12.2 How to assign a position angle to its correct quadrant. Note that for the purpose of using this table, the sign (+ or −) of $\Delta\delta$ is always taken from a transit carried out in the northern half of the field; otherwise the signs must be reversed.

$\Delta\alpha$	$\Delta\delta$	Quadrant	θ=
+	−	1 (0 - 90)	θ
+	+	2 (90 - 180)	180 - θ
−	+	3 (180 - 270)	180 + θ
−	−	4 (270 - 360)	360 - θ

The first transit of the star ΣI 57 recorded in Table 1 provides a convenient practical example. We can see that the difference in right ascension, $\Delta\alpha$, is given by (1):

$$\frac{(29.36+276.77)}{2} - \frac{(0.00+279.81)}{2} = 13.16 \text{ seconds}$$

Let us now calculate the difference in declination between the two components. The first step is to find the angles γ_A and γ_B. Consulting our catalogue, we find that the declination (2000) of ΣI 57 is +66°.7333 (this refers to the A component). The radius of the ring used to make the observation was 916″ . Therefore:

$$sin\gamma_A = \frac{7.5205 \times cos 66 \deg .7333 \times (279.81 - 0.00)}{916} = 0.9075$$

from which it follows that γ_A itself must be 65.16. By the same method, we find sin γ_B to be 0.8024, and γ_B = 53.36 (note that at this stage, in the absence of an accurate figure, we have had to treat the declination of B, δ_B being equivalent to that of A, Δ_A.

Applying equations (12.5) and (12.6), the distance in declination of A from the centre of the field is:

$$916 \times \cos 65^\circ.16 = 384''.80$$

and that of B:

$$916 \times \cos 53^\circ.36 = 546''.66$$

It therefore follows that according to this preliminary calculation, the difference in declination between the two stars is:

$$384''.80 - 546''.66 = -161''.86$$

Since this transit took place north of the field centre, the minus symbol in the answer tells us that B lies north of A. Now, Σ I 57 is a northern hemisphere pair. Hence, in order to obtain B's declination, we need to add $161''.86$, or $0^\circ.0450$, to that of A:

$$66^\circ.7333 + 0^\circ.0450 = 66^\circ.7783$$

[If your calculator does not have a facility for automatically converting degrees, minutes and seconds into decimal degrees, simply find the total number of arc seconds and divide by 3600.]

We are now in a position to refine our results by recalculating $\Delta\delta$, substituting the new value for Δ_B in equation (8). This gives a final figure of $163''.63$. We also convert our $\Delta\alpha$ figure into arc seconds, using the mean declination of both stars:

$$13.16 \times 15.0411 \times \cos 66.7558 = 78''.12$$

After repeating this process for each of the other transits, means are taken of $\Delta\alpha$ and $\Delta\delta$. In this particular case, the results are: $\Delta\alpha = 78''.37$ and $\Delta\delta = 164''.85$.

Applying equation (12.10), we obtain the the position angle: $\theta = 25^\circ.4$ and from equation (12.11), separation: $\rho = 182''.5$

Since $\Delta\alpha$ is positive (B following A), and B lies north of A), we see from Table 2 that in this particular case B lies in the first quadrant (0° - 90°), and no further correction to θ is necessary.

According to the WDS, this pair was actually measured by the Hipparcos satellite with the following results (1991): $\rho = 182''.4$; $\theta = 25^\circ$. It will be seen that our figures, which are based upon observations made in 1997, are remarkably close. This is certainly a fluke. As a rule, even a large number of transits is unlikely to produce results as seemingly impressive as these. In practice, if you can consistently get within 1° in position angle and 1'$''$ in separation, you will be doing very well indeed. In this particular case, the Zeiss ring micrometer was used on two nights to time six transits across the inner and outer edges of the ring, with the following overall result:

$\rho = 183''.5$; $\theta = 25^\circ.2$.

The position angle result is in full agreement with the Hipparcos figure, whereas the separation result differs from Hipparcos by less than 1%. This is fairly typical of the level of performance to be expected from the ring method.

For maximum accuracy, a total of not fewer than 10 transits should be taken, preferably spread over several nights. It is a good practice to take half the transits near the north edge of the field and the rest near its south edge, taking care not to apply the wrong sign (plus or minus) when calculating $\Delta\delta$. If you have a proper ring micrometer, record the times of appearance and reappearance at its outer and inner edges. In that way, you will be able to refine your results slightly by taking the mean of twice as many timings during each transit. My own experience, as can be seen from the example of Σ I 57, suggests that in this way it should be possible to obtain results to within about $1''$ of the true position. Although this is nowhere near good enough for measuring close doubles, it is perfectly acceptable for pairs wider than about 100″.

The rather involved mathematical process of reduction may seem daunting at first sight, but it need not be either laborious or complex if the observer uses a programmable calculator or computer. Once such a device has been programmed to carry out the tedious computations, results can be obtained almost as quickly as the raw timings can be keyed in.

The particular advantages of the ring method are that it requires no special apparatus beyond a stopwatch, needs no form of clock drive or field illumination, can be used with an altazimuth telescope as well as an equatorial and is capable of producing consistently accurate results on very wide pairs (separation greater than 100″). It may be worth bearing in mind that although wide and faint doubles lack the glamour of close and fast-moving binaries, they are probably in even greater need of measurement.

The drawbacks of the method, apart from the restriction of its accurate use to very wide pairs, are the rather time-consuming nature of the observations and the elaborate process of reduction. These, although they are greatly reduced by the use of a computer or programmable calculator, can never be entirely eliminated. A Delphi 5 program to carry out this reduction, written by Michael Greaney, is available on the accompanying CD-ROM.

12.3 The chronometric method

The chronometric method allows a significant increase in accuracy over the ring method. Of comparable antiquity, it requires the addition to the telescope of an external position circle or dial, as well as a single wire or thread mounted at the focus of the optical system. A motor-driven mount is, if not an absolute necessity, at any rate highly desirable. Since position angles are measured directly with the circle, the chronometric method is a hybrid technique rather than a pure transit method. The sole purpose of the timed transits is to obtain differences in right ascension, from which it follows that no calibration exercise is necessary.

An ordinary crosswire eyepiece will serve admirably as the basis of the micrometer. If no such eyepiece is available, a single thread or wire can be mounted in the focal plane of a positive eyepiece, preferably one having a relatively short focal length. The thread must be as fine as possible, ideally no more than 15 microns in diameter. Various materials have been suggested, including nylon or spider's thread. In order to render such materials visible against the dark sky background, some means of illuminating either the field or the thread is essential. A small torch bulb or light-emitting diode may be installed near the objective or inside the eyepiece or Barlow lens. A potentiometer can also be provided so as to enable the observer to vary the level of illumination. Alternatively, at the cost of some degree of precision, the need for a source of illumination may be dispensed with altogether by making the wire relatively thick. I have used a length of 5-amp fuse wire for this purpose.

The wire must be stretched diametrically across the field stop and glued in position. The most difficult part of fitting the wire is to keep it under tension so as to ensure that it is perfectly straight. Even then, it is likely to prove rather a crude substitute for an illuminated thread or field.

The position circle or dial can be made from an ordinary 360° protractor, which is fitted to the focussing mount. It must be carefully centred on the eyepiece, to which a pointer or vernier index is attached. The dial must be capable of adjustment by rotation about the optical axis. It is graduated anticlockwise unless the optical system reverses the field, in which case the dial should be graduated in the opposite sense.

Although there is no need to calibrate the micrometer, it is necessary to establish the circle reading that corresponds to north (0°) before measurement begins. One way of achieving this is to find a star near the equator and allow it to drift across the field of view, rotating the eyepiece until the star accurately trails the single thread. Then, leaving the eyepiece undisturbed, adjust the position circle until the pointer indicates a reading of 270° (west). Provided the circle is correctly graduated, it will follow that the zero reading indicates celestial north. By this method, position angles of double stars can be read directly from the PA dial without the need for any correction. However, it is practically impossible to exclude all sources of error in such a home-made device. Quite apart from any defects in the protractor itself, it is unlikely to be perfectly centred on the optical axis. In order to overcome such sources of error, Courtot(1) has recommended the following alternative approach. Adjust the web so that a star drifts along it when the motor is stopped, and note the reading on the dial. Then rotate the eyepiece through 180° , so as to minimise the effects of any centering error, and repeat the process, this time subtracting 180° from the reading. Proceed in this way until you have gathered six readings, and take the mean. The difference between the result and 90° gives the north angle.

Let us illustrate the procedure by reference to Courtot's own example. Suppose that by repeatedly drifting a star along the web we obtain the following circle readings:

Table 12.3 Determination of drift PA

East	92.2	West	273.3
	92.5		273.0
	92.3		273.1
	——		——
Mean	92.33		273.13

Subtract 180° from the mean west result:

$$273^\circ.13 - 180^\circ = 93^\circ.13$$

Hence the overall mean is:

$$\frac{(92\,\text{deg}.33 + 93\,\text{deg}.13)}{2} = 92\,\text{deg}.73$$

Since this corresponds to the true position angle 90° , the north angle is: 92°.73 - 90° = 2°.73

This angle is a correction which will be applied to all subsequent circle readings.

To obtain the position angle of a double star, carefully rotate the eyepiece until the wire is precisely parallel to the pair's axis and note the reading of the PA dial. Then reverse the pointer through 180° and take another measurement. The entire process should be repeated until a total of at least 6 readings have been obtained. Of these, half will have to be adjusted by 180° . Take the overall mean, remembering to correct for any north angle.

The observer obtains the separation of the pair by timing transits across the wire. At least 20 such timings should be made. There are several variations in the procedure. The simplest way is to set the wire exactly NS, so that the interval in the times of passage across the wire of the two components corresponds to the difference in RA. The separation is then given by:

$$\frac{15.0411 \times t \times cos\ \delta}{sin\ \theta} \qquad (12)$$

in which t is the mean interval in seconds, δ is the declination of the pair and θ its position angle.

For example, on the night of 2001 August 26, I measured the well-known pair 61 Cyg, with the following results: θ = 149°.9, t = 1.3384 seconds

Since the declination of 61 Cyg is 38°.75, the separation, ρ , is given by:

$$\frac{15.0411 \times 1.3384 \times cos\,38.75}{sin\ 149.9} = 31''.3$$

In the case of pairs having a PA close to 0° or 180° , both components will transit the wire more or less simultaneously. There are two ways of overcoming this difficulty. One is to set the web at exactly 45° to the direction of drift (see Fig. 3), remembering to take into account the north angle. Then, assuming the web is orientated 135° /315° as shown in Fig. 12.3, the separation is given by:

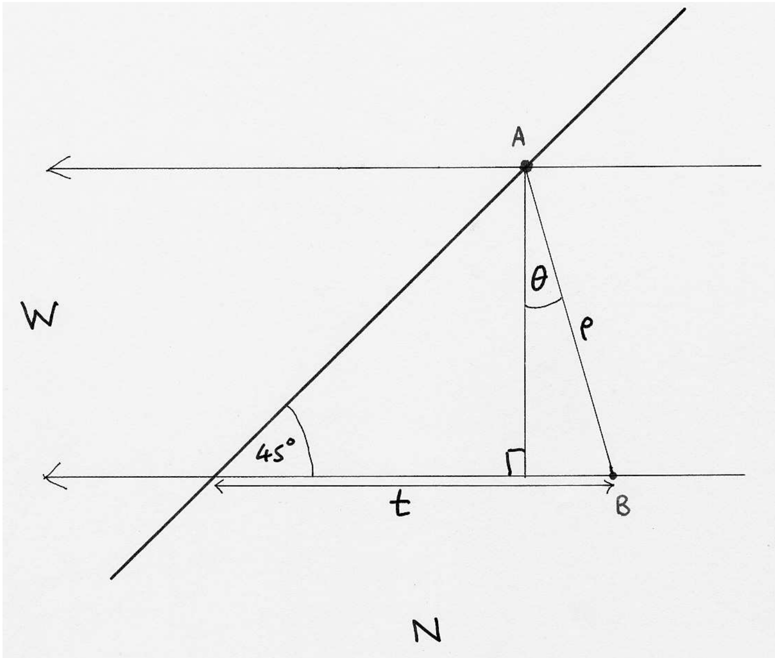
$$\rho = \frac{15.0411 \times t \times cos\delta}{(cos\theta + sin\theta)} \qquad (13)$$

If the web is orientated 45° /225° , the separation is:

$$\rho = \frac{15.0411 \times t \times cos\delta}{(cos\theta - sin\theta)} \qquad (14)$$

Courtot(1) has suggested an alternative procedure in which the web is placed approximately perpendicular to the pair's axis. The angle, i, between the wire and the direction of drift is read from the circle (making allowance for any north angle).

Fig. 12.3 With the wire set at 45 degrees to the direction of drift, measure the elapsed time between the transits of star A and B on the wire.



It is positive, increasing from east through south and so on (Fig. 12.4). With the telescope clamped a short distance west of the pair, use a stopwatch to measure the time taken for both components to cross the thread. Repeat the process at least 10 times, noting the results to two decimal figures. Then reverse the wire 180° and take another 10 timings.

These timings, together with the declination of the pair and the position angle already determined from the PA dial, enable the observer to deduce the separation, ρ, of the two components :

$$\rho = \frac{15.0411 \times t \times cos\ \delta \times tan\ i \times tan\ \theta}{sin\ \theta \times (1 + tan\ i \times tan\ \theta)} \qquad (16)$$

Using Courtot's own example, suppose that the mean transit interval, t, is 2.386 seconds and the declination of the star is 25°.25. The position angle, θ, has already been measured as 223°.04. Let us further suppose that for the purpose of timing the transits, the web was set with a circle reading of 135° , which corresponds to 45° starting from east. After subtracting the north angle, 2°.73, we find that the web was actually set at i = 45 - 2.73 = 42°.27 from east. Then, applying equation (12.16):

$$\frac{15.0411 \times 2.386 \times cos\, 25.25 \times tan\, 42.27 \times tan\, 223.04}{sin\, 223.04 \times (1 + tan\, 42.27 \times tan\, 223.04)} = -21''.8$$

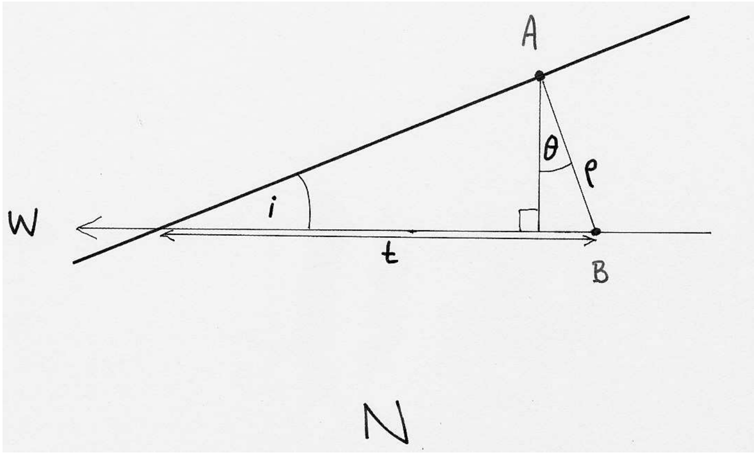


Fig. 12.4 Using Courtot's method with the wire approximately perpendicular to the orientation of the pair.

The negative value of ρ merely indicates that the companion is west of (preceding) the primary, and the minus sign is therefore ignored.

The main advantage of the chronometric method is that it has greater accuracy than the ring method and can handle pairs down to a separation of as little as 15″. By the careful use of Courtot's variation, this limit may be reduced still further - perhaps even below 10″. Because each transit lasts only a few seconds, it is a relatively quick technique. The reduction procedure, while still somewhat elaborate, is far simpler than the ring method, although the advent of modern electronics has greatly reduced this difficulty in respect of both techniques.

The principal disadvantage of the chronometric method is that for reliable results it demands the use of an equatorial mount. Indeed, it is highly sensitive to misalignment of the mount. If significant errors in position angle are to be avoided, the polar axis of the mounting must be accurately set on the celestial pole, with an error of 1' or less. It follows that the chronometric method is better suited to permanently mounted telescopes than to the portable instruments favoured by many amateurs. Another drawback is that the use of a fine filament necessitates the provision of some form of field or web illumination, which in turn necessarily reduces the working magnitude threshold of the telescope.

12.4 Illuminated reticle eyepieces

There are now readily available a number of proprietary eyepieces which are supplied by their manufacturers with illuminated reticle systems. They have completely transformed amateur double-star astrometry(2). The Celestron Micro Guide eyepiece provides a typical example, but other makes are essentially similar (this section refers specifically to the Celestron version). Reticle eyepieces of this type require the use of a motor-driven equatorial mount, with remote slow-motion controls to both axes. This section describes two methods of using the Micro Guide. The first is simple yet very effective, while the more advanced procedure is considerably slower but promises even greater accuracy.

The Celestron Micro Guide is an orthoscopic eyepiece of 12.5-millimetre focal length incorporating a laser-etched reticle and a battery-powered variable illumination system (Fig. 12.5). The Meade version uses a different reticle layout (Fig. 12.6). In both cases, however, there is a 360° protractor scale at the edge of the field and a linear scale at the centre. The linear scale, which is used to measure separation, is a ruler graduated at 100-micron intervals. Position angles may be determined either by means of an external position circle or, more elegantly and more simply, by using the drift method described in this section.

The first step is to calibrate the linear scale by determining the scale constant, i.e. the number of arc seconds per division. The smaller the constant, the more accurate the measures will be. This dictates as great an effective focal length as possible. Ideally, the focal length should be 5 metres or more, and certainly not less than 3 metres. Since most amateur telescopes have a focal length of between only 1 and 2 metres, it is obvious that a Barlow lens will usually be necessary in order to amplify the image scale at the telescopic focus.

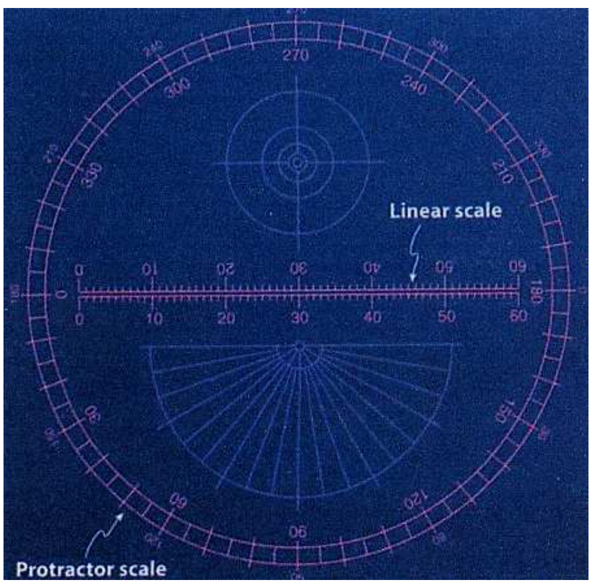


Fig. 12.5 The reticle of the Celestron Micro-Guide eyepiece. The thickness of the inscribed lines and circles is 15μm.

To calibrate the eyepiece, time the passage of a star along the entire length of the linear scale. Select a star that is neither too bright nor too faint - magnitude 5 or 6 will probably be about right for small or medium apertures. In order to minimise the effects of timing errors, choose a star of relatively high declination, but without straying too close to the celestial pole. I have found that a declination of between 60° and 75° is suitable. Rotate the eyepiece until the star drifts exactly parallel to the linear scale. Then use a stopwatch to time the star's journey from one end of the scale to the other. Repeat the process at least 30 times, preferably spread over several nights, and take the mean. To convert the result into arc seconds, multiply by 15.0411 cos δ, where δ is the star's declination. Then divide by the number of divisions in the scale; in the case of the Micro Guide this is 60, but the equivalent scale in the Meade version has 50 divisions. The resulting scale constant, z, will always remain valid for the same optical set-up.

The simpler of the two methods of measuring the separation of a double star is as follows. Rotate the eyepiece until the linear scale is exactly parallel with the pair's axis, ensuring that the primary star is closer to the zero point (or the 90° point in the Meade version) on the 360° protractor scale; although this precaution has no bearing on the separation measure, it will assume importance when it comes to measuring the position angle at a later stage. Then, estimating to the nearest 0.1 division, count the number of divisions separating the two components and multiply the result by the scale constant to obtain the separation in arc seconds.

Measuring the position angle is a slightly more involved process. One way of going about it is to use an external position circle or dial as described in the previous section, but this is actually quite unnecessary(3). By allowing a star to drift across the field, it is possible to obtain accurate position angles from the 360° protractor scale etched on the reticle itself.

The procedure is as follows: having completed the separation measure, leave the motor running and the orientation of the eyepiece undisturbed so as to preserve the alignment of the reticle. Use the slow-motion controls to bring a star to the exact centre of the field, which on the Micro Guide will be found to lie between the "30" markings on the linear scale. For this purpose, any convenient star will do; it does not even have to be a component of the pair being measured. Once the star is accurately centred, switch off the motor drive and allow the Earth's rotation to carry the star towards the western edge of the field of view. The direction of drift, by definition, corresponds to the true position angle 270° . When the star reaches the 360° protractor scale, switch the motor on and read and record the angle indicated by the star on the protractor scale (Fig. 12.7). For a conventional inverted field, the outer (clockwise) set of figures should be used. The inner (anticlockwise) figures are for use with a reversed image, as produced by a right-angle prism. Although the scale is only graduated at intervals of 5, it is perfectly feasible to estimate to the nearest 0°.5, which is sufficient for all practical purposes.

Subject to one possible correction, the reading indicated by the star shows the position angle of the pair. When using the Celestron Micro Guide, it is necessary to add 90° to the protractor reading in order to arrive at the true position angle. If the final result exceeds 360, just subtract 360 to bring the answer within the range 0 - 360. With the Meade version, which employs a different layout, no correction is necessary.

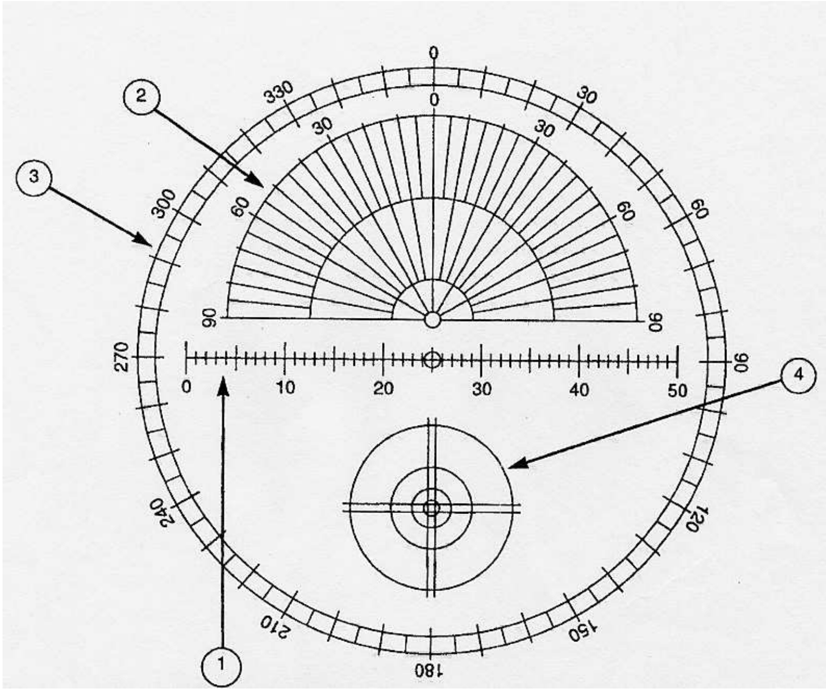


Fig. 12.6 The reticle of the Meade astrometric eyepiece

As with other techniques of measurement, observations should be repeated over a number of nights and means taken. Used in this way, a reticle eyepiece is capable of making good measures of pairs of any separation lying comfortably within the telescope's resolving ability. It is important to eliminate the effects of parallax by ensuring that the reticle and the star images are focussed in exactly the same plane. To achieve this, adjust the telescope focus and the eyepiece dioptre control until you can move your head from side to side without inducing any relative movement between image and reticle.

The beauty of the drift method is that it effectively eliminates index error and places considerably less stringent demands upon the accuracy of the mount's alignment by comparison with a conventional position circle. It follows that this particular technique of measurement lends itself especially well to portable equatorials. Perhaps for that reason, it has become steadily more popular among amateur observers since it was first described in print (3).

In an alternative, more advanced procedure, the observer uses the reticle eyepiece to measure pairs of angles in each of which both components of the pair are bisected by markings on the linear scale. Employed in this fashion, the eyepiece effectively becomes a degenerate form of filar micrometer. It is a method which produces greater accuracy in the measurement of separation, but it is also slower than the basic procedure already described.

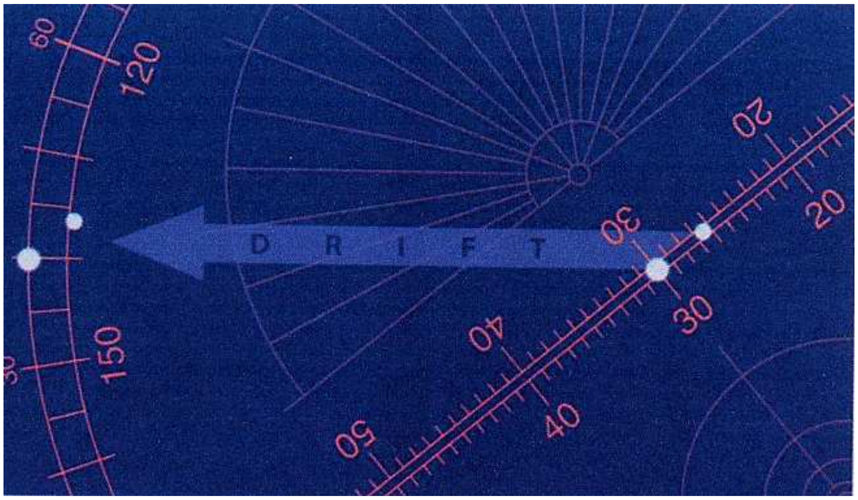


Fig. 12.7 Using the simpler method, the pair's separation is measured against the linear scale. The position angle can be found by switching off the telescope's clock drive until the pair drifts to the protractor scale, where the angle is noted. It is important not to bypass or hasten the drift process by using the telescope's RA motor, as unless the polar alignment is perfect, the result will be incorrect. Reproduced courtesy of Sky Publishing Corporation

The first step is to rotate the eyepiece until the linear scale is parallel with the axis of the pair to be measured, remembering to ensure that the primary star lies closer to the zero point on the 360° protractor scale. The observer counts the number, n, of whole divisions on the linear scale separating the two components. In the example illustrated in Fig. 12.7, it will be seen that n = 3. With the motor drive running, the eyepiece is rotated and the slow-motion controls adjusted until a pair of scale markings n divisions apart bisects the two stars as shown in Fig. 8a. Leaving the orientation of the eyepiece undisturbed, the observer uses the slow-motion controls to bring a star to the exact centre of the field, turns off the drive and notes the angle, θ_1, indicated by the 360° protractor circle at the point where the star drifts across it. In figure 12.8(a), the reading is 60° .

Next, the eyepiece is rotated in the opposite direction, past the original position at which the axis and linear scale are parallel, until both components are once more bisected by two markings on the linear scale (see Fig. 12.8b). Again, the observer measures the angle, θ_2, as before. In the example shown, the reading is 20° .

If one of the two angles happens to fall within the first quadrant (0° - 90°) and the other in the fourth quadrant (270° - 360°), add 360 to the lower of the two figures. This is necessary in order to avoid numerical complications at a later stage in the process of reduction.

The position angle of the pair, θ, is given by the mean of the two angles:

$$\theta = \frac{\theta_1 + \theta_2}{2} \qquad (17)$$

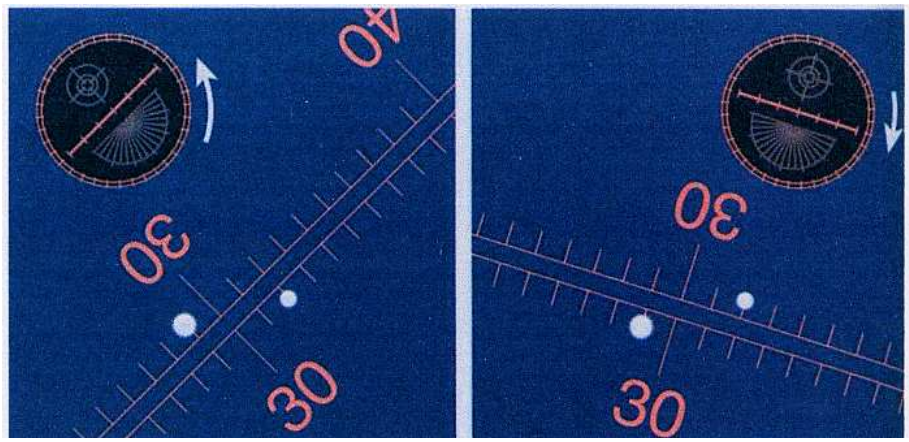


Fig. 12.8 The advanced method: (a) measuring θ_1; (b) measuring θ_2

to which (in the case of the Celestron version) the 90° correction must be added. The separation, ρ , is given by:

$$\rho = \frac{n \times z}{cos\ \alpha} \qquad (18)$$

where *n* represents the number of whole divisions separating the components, *z* the scale constant, and is half the difference between the two angles θ_1 and θ_2 :

$$\alpha = \frac{\theta_1 - \theta_2}{2} \qquad (19)$$

In the example shown, α = 20° . Assuming a scale constant, z, of 5″ , the corresponding separation is therefore

$$\frac{3 \times 5}{cos\ 20} = 15''.96$$

Again, the procedure should be repeated over a series of nights and means taken of the position angle and separation. In each set of observations, it is a sensible practice to include a number of direct determinations of the position angle made by the simple method, as shown in Table 3.

Table 12.3. This observation of Σ1442 was made on 2000, Mar 25 with a 21.5-cm Newtonian reflector and Celestron Micro-Guide eyepiece (z = 6″.25). Each set of measures occupies a numbered row. The first angle is θ_1, the next a direct PA measure theta made by the simple 'drift' method, and the third θ_2; note all these angles appear in their uncorrected forms. The penultimate column shows the corrected position angle, obtained by adding 90 eto the mean of the three preceding entries. The final column gives the separation, derived

Table 12.4 This observation of $\Sigma 1442$ was made on 2000, Mar 25 with a 21.5-cm Newtonian reflector and Celestron Micro-Guide eyepiece ($z = 6''.25$). Each set of measures occupies a numbered row. The first angle is θ_1, the next a direct PA measure θ made by the simple 'drift' method, and the third θ_2; note all these angles appear in their uncorrected forms. The penultimate column shows the corrected position angle, obtained by adding 90° to the mean of the three preceding entries. The final column gives the separation, derived from θ_1 and θ_2 by the method described in the text. The overall mean position angle and separation appear in the last row.

	θ_1	θ	θ_2	θ	ρ
1	45	68.5	85	156°.17	13″.30
2	49	66	88.5	157°.83	13″.28
3	43	66	94	157°.67	13″.85
4	48	67	89	158°.00	13″.35
				157°.42	**13″.45**

from θ_1 and θ_2 by the method described in the text. The overall mean position angle and separation appear in the last row.

Because this method of using a reticle eyepiece is insensitive to variations in ($\theta_1 - \theta_2$), it is capable of yielding separation measures far more accurate than those obtained by means of the standard technique. In theory, the precision is not constant, since the uncertainty increases with α. But since it is easier to judge simultaneous bisection at high values of α than at lower values, the competing practical and theoretical considerations probably cancel out.

The range of measurement is restricted by the layout of the reticle. For obvious reasons, the lower limit is set by z, the value of the scale constant. However, it is possible to measure closer binaries by turning the eyepiece through 90° and bisecting the stars with the two long parallel lines, which are only 50 microns apart. Provided the line nearer to the semicircular protractor scale always bisects the primary star, this expedient will also remove any need for a 90° correction; in the case of the Meade version it will, of course, introduce such a correction.

It is the inconveniently short graduation markings on the linear scale that impose an upper limit on the range of continuous measurement. At certain separations beyond about 6z, the observer will find it impossible to bisect both components simultaneously, with the result that gaps begin to appear in the measurement range. For wider pairs, the Barlow lens may always be dispensed with, but this will require the reticle to be recalibrated.

The more advanced method of using an illuminated reticle eyepiece places extreme demands on the observer's patience and dexterity. Not everyone will find the gain in accuracy is really worth the extra time and effort. While it may be useful for occasional measurements, where time is not a consideration, or for the observer who has to make do with a relatively short effective focal length, the amateur who wishes to pursue a systematic programme involving the study of as many pairs as possible will probably prefer to master the simpler technique in conjunction with a telescope having an effective focal length of not less than 5 metres.

Irrespective of the procedure adopted, the illuminated reticle enjoys great advantages over other methods. It is readily obtainable at a reasonable cost. It is capable of considerable accuracy (4). It eliminates index error, is comparatively tolerant of errors in polar alignment and is, therefore, particularly suitable for portable instruments. Its main disadvantage lies in the raising of the magnitude threshold by reason of the illumination system.

12.5 Practical recommendations

Subject to the individual limitations already summarised, any one of the three methods discussed in this chapter is capable of producing results of publishable accuracy. The first two are of particular interest to those who do not wish to buy special equipment. The ring method, although confined to very wide pairs, is ideal for the beginner who wants to attempt measurement without investing in expensive accessories. The chronometric method is more accurate, can handle closer pairs and is perhaps especially suitable for those who enjoy making their own equipment.

For all other purposes, however, the illuminated reticle eyepiece is superior.In the absence of a filar micrometer or equivalent professional apparatus, the observer intending to embark upon a serious programme of visual measurement, with a view to publishing the results will undoubtedly an the illuminated reticle eyepiece the most practical option.

12.6 References

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Chapter 13
Filar micrometer

Bob Argyle

Introduction

The measurement of double stars is central to the theme of this book and there are many ways of doing this, but this chapter is dedicated to the use of the filar micrometer which has been used seriously since the time of William Herschel. (For a thorough discussion of the history and development of the filar micrometer see the paper by Brooks (1)).Much of our knowledge of longer period visual binaries depends on micrometric measures over the last 200 years. The filar micrometer is by far the most well-known device for measuring double stars. Its design remains largely the same as the original instrument which was first applied to an astronomical telescope by the Englishman William Gascoigne (c.1620-1644) in the late 1630's. The aim is to use fine threads located in the focal plane of the telescope lens or mirror to measure the relative position of the fainter component of a double star with respect to the brighter, regarding the latter as fixed for this purpose. This is done by the measurement of the angle which the line joining the two stars makes with the N reference in the eyepiece and the angular separation of the fainter star (B) from the brighter (A) in seconds of arc. These quantities are usually known as theta (?) and rho (?) respectively and are defined in Chapter 3.

The basic filar micrometer consists of two parallel wires, one fixed, one driven by a micrometer arrangement, with a third fixed wire at right angles to these two. (Fig. 15.1). The movable wire must be displaced in the focal plane just far enough from the other two such that it can move freely and yet be in focus. It must also, of necessity, be very thin, preferably smaller than the apparent size of the star disks through the eyepiece. If the focal length of the telescope is too short then a Barlow lens is necessary. This has the advantage of boosting the focal length by 2 or 3 times and yet has no effect on the apparent size of the thread.

The usual material for the wire is spider thread which was chosen for its fineness and relative ease of availability. (In fact it was a spider making its web in one of his telescopes that gave Gascoigne the idea for the filar). Replacing spider thread in a micrometer is a relatively skilled job and these days commercially available micrometers use tungsten with a thickness of about 12 microns. The micrometer used by the author has been in regular use for 10 years and the wires have remained correctly set throughout, even though the micrometer has been fitted and removed from the telescope hundreds of times and many thousands of individual settings of the wires made.

Fig. 15.1 The arrangement of wires in a modern filar micrometer

In the modern Schmidt-Cassegrain the Barlow lens is a particularly useful accessory. For a 20-cm f/10, for instance, the focal length of 2000 mm is equivalent to a linear scale at the focal plane of 103 arc seconds per mm. This means that a 12 micron wire will subtend a diameter of about 1.25 arc seconds. This is about twice the angular resolution of the telescope so it would limit the user to measuring pairs wider than about 3.0 arc seconds. Even then the thickness of the threads would make accurate centreing of star images difficult.

The body of the micrometer must be able to rotate through 360 degrees and its angular position is accurately measured by a circular gauge known as the position angle circle. This is usually graduated in degrees with a vernier available to read to 0.1 degree.

In the classical brass micrometer, another arrangement called the box screw is usually included. This allows both the fixed and movable parallel wires to be shifted in the focal plane by the same amount. This is useful when the double distance method of measuring separation is employed (described more fully later). For micrometers without this facility (and this tends to include the modern instruments that have become available over the last few years) it is necessary to move the whole telescope to bring the threads into position for double-distance measurement. Alternatively, the method described by Michael Greaney(2) obviates the need to move the whole telescope

After setting the movable wire on the companion and noting the reading, the micrometer is rotated around 180 degrees so that the PA wire bisects the two stars again. The micrometer screw is then turned to move the movable wire across the primary back to the companion. The new reading is then noted and the difference between the two readings gives a measure of the double distance.

As the PA wire bisects the two stars a second PA reading can be taken. Add 180 degrees to this second PA reading if it is less than 180 degrees, or subtract 180 degrees if it is more. The mean of the first and (corrected) second PA readings can be taken as the PA reading for that particular measurement.

Determination of the screw constant

This is a rather more difficult task since it is first necessary to determine what the angular equivalent of the linear motion of the micrometer screw is. In the example above we saw that the 20-cm f/10 Schmidt-Cassegrain has a linear scale of 1 mm = 103 arc seconds at the principal focus so that if the micrometer has a screw pitch of 0.5mm per revolution then each rotation of the screw moves the wire 56.5 arc t

Fig. 13.1 Fig. 15.2 A RETEL micrometer fitted to the 8-inch refractor at Cambridge. The Barlow lens assembly is the brass tube immediately above and the power supply for the field illumination is attached to the tube within reach of the eyepiece. Comfortable observing positions such as this are rare. The chair collapsed entirely soon after this picture was taken!

seconds. It is necessary to subdivide the screw into usually 100 smaller intervals with visual estimates of perhaps one-tenth of each division giving values to 0.001 revolution or 0.06 arc seconds in this case. It is necessary to determine this screw value and not to take the manufacturers data for the focal length of the telescope and Barlow lens. Note however that in those telescopes were the primary mirror is moved to adjust focus then this alters the scale constant and it is therefore important that the scale calibration is checked regularly.

Transits

A commonly used methods involves using star transits - but on stars at high declination. With a hand held stopwatch time the transit of a star across the movable wire and note the corresponding value of the micrometer screw. Move the micrometer screw by a fixed amount, say 0.5 or one revolution in the direction of the star trail, and time the next transit on the wire. Repeat this for as many revolutions as possible, It will then be possible to calculate a value for one revolution of the screw from all the individual measures. For a star at declination +75 for instance the motion of the star is 15 cos 75 arc seconds of time per second so it will take 56.5/15 cos 75 seconds = 14.6 seconds of time to travel the equivalent of 1 revolution of the micrometer screw in the standard Schmidt-Cassegrain described above. This should be timed to better than 0.5 seconds of time but taking the mean of n revolutions will increase the accuracy of the mean figure by a factor of n. The timings should be repeated on other nights to confirm the figure reached. Further checks at regular intervals are also recommended - to see if there is any variation of the screw constant with temperature or with time (due to wear and tear).

Calibration pairs

Another way of evaluating the screw constant is to measure wide, bright pairs whose position angles and separations are well known and relatively fixed. It will be necessary to have up to a dozen of these pairs spread around the sky so that one can be observed at any time of the year. I use this method and in Appendix 4 I give a list of pairs with relative positions predicted for 2000.0, 2005.0 and 2010.0. As these pairs change only very slowly the positions for future years can be done by simple interpolation.

Making an observation with a filar micrometer

13.0.1 Position angle

The measurement of position angle is easiest to make and is usually done first since the measurement of separation depends on the separation wires being perpendicular to the line joining the two stars (Fig. 15.1). Position angle is defined as 0° when the companion is due north of the primary, 90° when it is due east and so on. The orientation of the position angle wire can be determined on the sky by several methods; the most common is to set the telescope on an equatorial star, allow the star to drift across the field and rotate the micrometer until the star drifts exactly along the position angle wire. Repeat at the end of the night and the mean of the two values will give the correction to be applied to all readings of position angle made during the night. If for instance at the start of the night the] reading is 89°.2 and at the end it is 88°.8 then the mean value of 89°.0 means that +1°.0 needs to be added to each mean position angle taken during the night. Even if the micrometer remains on the telescope it is worth doing through this procedure each night.

The measurement of position angle involves setting the PA wire to lie across the centre of the images of each star. It may be difficult to see a faint star under the wire but an alternative of setting the wire tangentially to the two star images is not to be recommended. Another possibility is to use the fixed and movable separation wires set slightly apart, turning them until the line between the stars is parallel to the wires. In this case the exact angle between these wires and the position angle wire needs to be known but once established should remain fixed until the threads need to be replaced.

If using the single position angle wire, it may be necessary instead to turn down the illumination so that the companion can be seen. Several measures of angle should be made depending on the brightness and separation of the pair but it is good practice to move the wire well away from the last determination before making the next measure. This should mean that the readings will be more independent.

It is as well if you are familiar with the position of the cardinal points for the telescope in use. The final position angle, being the mean of each independent setting, may need to be corrected by 180 degrees depending on the quadrant in which the fainter star lies. Remember that in Schmidt-Cassegrain telescopes the cardinal points are a mirror reflection of those in Newtonians and refractors. The use of star diagonals will also add a mirror inversion.

As mentioned above, pairs of accurately known separation and position angle can also be used to calibrate the position angle circle on the sky and a list of some bright ones is given in Table 1.

13.0.2 Separation

The most common technique for the measurement of distance is called the ’double-distance’ method. (see Fig 15.3). Basically the fixed wire of the micrometer is placed on the primary star and the movable wire on the companion. The reading of the movable wire is noted. The telescope and micrometer screw are then moved until the fixed wire is placed on the companion and the movable wire placed on the primary star. The difference between the two positions of the screw is twice the separation of the pair in millimetres (or whatever unit the screw is calibrated in). This is repeated several times, depending on the difficulty of the pair. The separation of the pair in arc seconds is then calculated by k (r2 - r1)/2 where k is the screw constant and r1 and r2 are the mean values of each separation setting. I make 4 double distance measures for wide pairs and up to 6 measures for close pairs. This procedure, like that of the determination of position angle, is repeated for several nights before a mean value is determined for each. It is better to make the measures of separation close to the position angle wire, since if the separation wires are not strictly parallel then the measure of separation will be in error and in any case the images will be better near the centre of the field.

Fig. 15.3 Double-distance method of determining separation

An alternative method by Michael Greaney (4) is illustrated in Fig 15.4. The CD-ROM contains Delphi 5 programs for calibrating and using filar micrometers.

Fig. 15.4 Alternative double distance measurement. (Greaney)

Illumination

The best way of illuminating the field of the micrometer is to direct a low but variable light onto the wires - i.e. bright wire illumination. In some micrometers notably the RETEL which uses a red LED, the field is bright and the wires are seen in shadow. Whilst red is usually regarded as the colour least likely to reduce the effectiveness of the eye and distract the observer, some astronomers prefer a different arrangement. Paul Couteau uses a white light to illuminate the wires whilst Wulff Heintz prefers yellow. Observers will appreciate that white light is definitely not recommended for field illumination.

Calibration pairs

Here is a table of bright and wide pairs whose position angles and separations can be predicted with sufficient accuracy to calibrate a filar micrometer. The data used for this has been taken from the Observations Catalogue at USNO, courtesy of Dr. B. D. Mason. The Catalogue contains all published observations irrespective of accuracy so some of the measures have been excluded from consideration. Sixteen bright pairs have been chosen to cover the north, the equator and the south for all times of year. The southern pairs are considerably less frequently observed and the predicted positions are therefore less reliable.

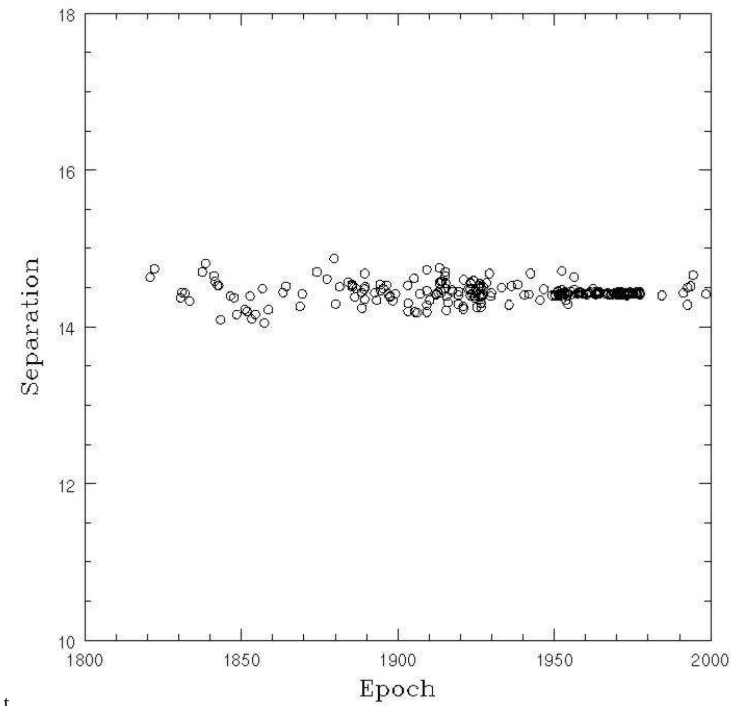

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Fig. 13.2 The measures of Mizar in separation 1820-2000

Although some of these pairs are real, if very slow-moving, binaries the observed arc is less than 5 degrees in most cases and so motion is assumed to be linear. A weighted, least-squares straight line fit to the data has been made in all cases with the weighting being made arbitrarily. It was decided to give micrometer measures a weight equal to the number of nights whilst photographic measures (and also Hipparcos and Tycho measures where applicable) were given a weight of 50. As an example Fig 15.5 shows the observations of zeta UMa (= Σ1744) from around 1820 to the present day, more than 350 in total. The effect of long sets of photographic measures made after 1950 is to dominate the fit but the earlier measures also fit the line reasonably well lending confidence to the predicted positions. In separation, there has been no significant change since observations began.

In each case in Table 1 it was first necessary to correct the observed angles for precession, bringing them up to the year 2000.0. The values given in the Table for future years, have also been corrected for precession to those epochs allowing an immediate comparison to be made with observations.

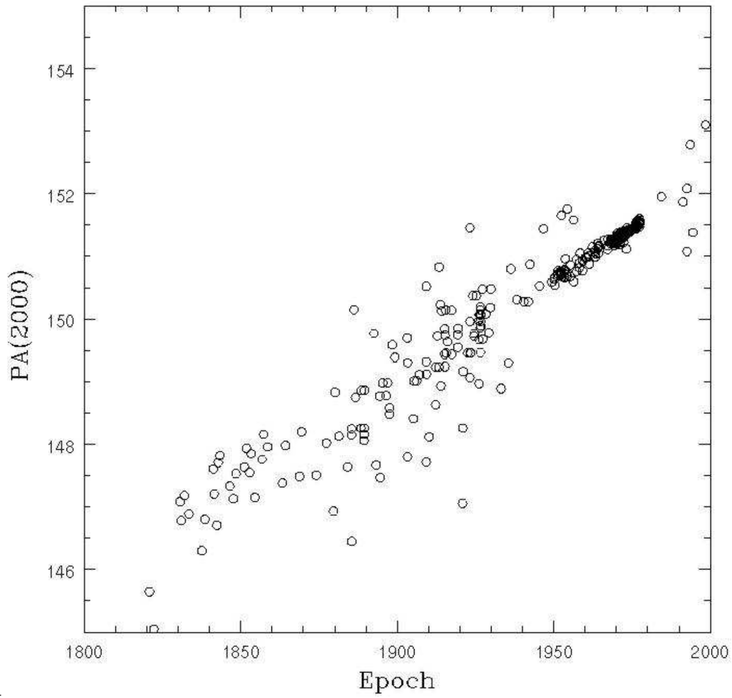

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Fig. 13.3 The measures of Mizar in position angle 1820-2000

Errors of measurement

When any quantity is measured errors can arise in the process. These can be two kinds. Firstly, random or accidental errors which are caused by natural fluctuation when making, for instance, a number of measurements of the separation of a double star with a filar micrometer. If you take say 6 readings at each position of the movable wire, the numbers will differ slightly. Taking the arithmetic mean of these numbers yields a figure which can be taken to be a fair representation of what the value being measured should be. This can be converted into an angular separation in the usual way. If the pair being measured is a binary star of known separation then if the same measurement is repeated on several other nights and the subsequent mean values all indicate a greater separation than expected then you may suspect the existence of a systematic error. It may be that the current orbit is not predicting the correct separation for the time of observation but it could also mean that the screw value for the micrometer is not correct. If the screw value is based on a single standard pair then there is room for systematic error to come in - it may be that the separation assumed is not correct. This can be tested by observing other standard pairs to see if the same screw value is obtained. If it is then the binary orbit can be suspected.

Table 13.1 A list of bright calibration pairs

Pair	RA (2000)	Dec (2000)	Mags	PA 2010	Sep 2010	PA 2015	Sep 2015	PA 2020	Sep 2020
β Tuc[a]	00 31.5	-62 57	4.4, 4.5	168.1	26.92	168.0	26.88	168.0	26.85
ζ Psc[b]	01 13.7	+07 35	5.2, 6.4						
θ Pic[c]	05 24.8	-52 19	6.3, 6.9	287.5	38.17	287.5	38.17	287.5	38.18
δ Ori[d]	05 32.0	-00 18	2.2, 6.8	0.2	52.42	0.2	52.42	0.2	52.42
γ Vel	08 09.5	-47 20	1.8, 4.3	220.4	41.21				
ι Cnc	08 46.7	+28 46	4.0, 6.6	307.5	30.49	307.5	30.49	307.5	30.50
Σ1627	12 18.2	-03 57	6.6, 7.1	195.5	19.87	195.4	19.83	195.3	19.79
24 CBe	12 35.1	+18 23	5.0, 6.6	270.3	20.62	270.2	20.75	270.1	20.88
α CVn	12 56.0	+38 19	2.9, 5.6	228.7	19.31	228.8	19.30	228.8	19.28
ζ UMa	13 23.9	+54 56	2.2, 3.9	152.6	14.45				
κ Lup	15 11.9	-48 44	3.9, 5.7	143.1	26.40	143.1	26.39	143.1	26.38
ν Dra	17 32.2	+55 11	4.9, 4.9	311.0	61.86	311.0	61.83	310.9	61.79
θ Ser	18 56.2	+04 12	4.6, 5.0	103.7	22.47	103.7	22.50	103.6	22.53
16 Cyg	19 41.8	+50 32	6.0, 6.3	133.2	39.62	131.2	39.67	131.1	39.71
o Cap	20 29.9	-18 35	5.9, 6.7	238.4	21.85				
β PsA	22 31.5	-32 21	4.3, 7.1	172.2	30.39				

[a] Both stars are close pairs in a large telescope
[b] The companion is a close pair in a large telescope
[c] The primary is a close pair in a large telescope
[d] The primary is a close pair in a large telescope

This is a particularly interesting and vital area which needs to be considered regularly if micrometric measures are to be regarded as stable and reliable.

Sources of error

- Positioning of wires on star
  The two graphs below illustrate the comparison of micrometer measures which I made (observed measures) with accurate measures of the same stars made with speckle interferometers and by the Hipparcos satellite and referred to below as the reference measures. When making these comparisons it is vital that the epochs of measurement agree as closely as possible, otherwise the comparisons are not valid due to orbital motion (or proper motion) during the interval.
  Fig. 15.6 shows the differences between the observed and reference separations. In this case the sense is (observed-reference) so that for the closest pairs (below about 1 arc second or so) the measured separations are too large. This is not an uncommon feature of measurement by micrometer and it is particularly useful for anyone doing orbital analysis. Whilst the raw measures are published as they stand, in the case of a particularly careful orbit calculation, it pays to try and assess the 'personal' error of the observers and then to apply correction to the observed positions. In practice this tends not to happen much because suit-

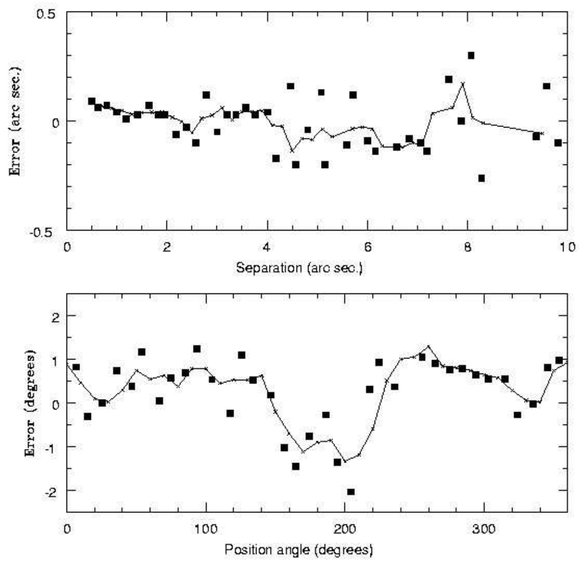

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Fig. 13.4 The error of a mean separation with separation. The solid line represents a running average

able reference measurements have not been available for comparison. This has changed for the better recently with the publication of the speckle results from the USNO (see the references in Appendix 1) where suitably accurate and up-to-date measurements are available to enable the observer to check his personal equation.

There is a large scatter at larger separations and this is due to a combination of the paucity of standards at these separations and fewer measures which I have made. Of the points in Fig. 15.6 some 210 pairs below 2 arc secs are compared, dropping to 69 pairs between 2 and 4 arc secs and only 31 pairs between 4 and 10 arc secs.

What can be seen from the graph in Fig. 15.6 is a tendency for me to measure the closest pairs (0.5 to 2 arc secs) as rather wider (about 10really are and from about 2 arc seconds and wider there is not much systematic error to be seen.

In Fig. 15.7 the graph shows the situation for the observed position angles for the same pairs as Fig. 15.4. Here there is clearly an anomaly at about PA 180 degrees.

This is where the two stars appear nearly vertical in the eyepiece. Although it is recommended to place the eyes either parallel to or right angles to the line between the stars it is more uncomfortable to do the former so I conclude that using the eyes parallel to the line between the stars results in an error in position angle of about -0.5 to -1 degree when the stars are within about 40 degrees of the vertical. Another way to avoid this is to use a prism in conjunction with the eyepiece to allow the field to be rotated by 180 degrees. By making another set of position angle measures here the mean value should then be free of this particular bias.

- Accuracy of reference pairs
  When using reference pairs to calibrate micrometers it is better not to use binaries because it is much easier to obtain accurate relative coordinates from wide pairs. In most cases these stars have been measured by Hipparcos or Tycho and there are plenty of measures going back over time which indicate any significant binary motion.
- Errors in the micrometer screw
  Each measure I make involves at least eight settings of the micrometer screw - typically 2,000 settings per year. It is reasonable to suppose that some wear and tear or backlash might make itself noticeable at some stage so regular checking should be made. This can be done by plotting the scale values derived from standard stars with time.

Availability of filar micrometers

For many years filar micrometers had been unobtainable and although the occasional classical brass example does appear they tend to get snapped up by collectors and placed on the shelf.

Over the last 15 years, however, a number of firms and individuals in the UK and USA have produced commercial instruments but it is believed that at the time of writing both these sources have dried up. The contact addresses are given below in case the reader wishes to ascertain the ltaest situation with production.

The RETEL micrometer is made in the UK from duralumin alloy and consists of a fixed and movable parallel wires and a PA wire at 90 degrees. The movable wire is driven by an engineering micrometer capable of about 12 mm of travel and readable to 0.001 mm using the vernier. The PA circle is calibrated in 1 degree intervals and again a vernier allows this to be improved to $0^\circ.1$. The wires are made from artificial fibre and are 12 μ thick which means that for short focus telescopes a Barlow lens is needed to reduce the apparent size of the wires in the eyepiece. Commercilaly available 8μ wire can be also be used to reduce the apparent size of the wire. The man-made fibre is extremely durable - I have had no breakages in 20 years of regular use involving many thousands of individual settings.

The van Slyke micrometer is made in the USA from a solid block of aluminium and again features an engineering micrometer to drive the movable wire whilst a range of optional extras such as digital readout are also advertised. Unfortunately, as this was being written the micrometer has been transferred to the manufacturer's discontinued catalogue but was still available as a custom order.

A comparison between the two made by Andreas Alzner can be found on the Webb Society web page (4).

13.1 References

(1) Brooks, R. C., 1991, Journal for the History of Astronomy, 22, 127.

(2) Greaney, M. P., 1993. Webb Society Quarterly Journal, 94, page.

(3) Greaney, M. P., 1994 Webb Society Quarterly Journal,

(4) Alzner, A., (http://www.webbsociety.freeserve.co.uk/notes/dsretel.html)

The RETEL micrometer is available from Retel Electro-Mechanical Design Limited, 22 Abingdon Road, Nuffield Industrial Estate, Poole, Dorset, BH17 0UG, UK. Contact Mr. L. Reynolds: tel (01202) 685883, Fax (01202) 684648.

The van Slyke Engineering Filar micrometer is still available on special order - see http://www.observatory.org/turret.htm

Chapter 14
The Diffraction Grating Micrometer

14.1 Introduction

Diffraction influences telescopic images by the effect it has on incoming starlight as we have seen in Chapter 10. It can also be used as the basis for a simple micrometer.

When it comes to measuring the position angles and separations of double stars, sophisticated and expensive precision instruments usually come to mind. However, if you can accept a limited selection of double stars then accurate measurements with very simple devices, the so-called diffraction grating micrometers, are possible. These micrometers, especially in their simplest forms, are very easy and inexpensive to build.

When a telescope object glass or mirror is masked by a coarse grating as shown in Fig. 14.1, diffraction of each star image will produce an array of satellite images on both sides of the star in a line perpendicular to the grating slits (Fig. 14.5a). The brighter the star and the wider the grating slits, the greater the number of visible satellites. These satellite images are actually rectangular-shaped spectra but this is only apparent with brighter stars. The central image is the zero order image, the neighbouring satellites are the first order images and so on. For measurement purposes though, only the zero and first-order images of each component are of interest. The basis of this micrometer is that the distance between the zero and first order images is fixed for a given grating and depends on the separation of the slits. For a given grating therefore, this distance, once determined, can be used to measure both the position angle and separation of double stars.

Experience has shown with gratings whose slit width is equal to the bar width give the best results because this corresponds to the maximum brightness of the first-order images. The critical dimension of a grating is the slit distance, p. The angular separation in seconds of arc between the zero and first order images is given by:

where l is the grating slit width (in mm) and d is the bar width (also in mm), so that p = (l + d). The wavelength of the starlight, λ , varies from about 5620 Å(5.62 x 10^{-4} mm) for an early B star to 5760 Å(5.76 x 10^{-4} mm) for an early

Fig. 14.1 The author's 20-cm Schmidt-Cassegrain equipped with a 50-mm grating. The first-order images are 2.3 arc seconds from the zero-order image. See also Fig. 14.5a. The position angles can be read on a 360 degree scale

M star but these values depend slightly on the observer and so λ is known as the effective wavelength. To use the micrometer to its full accuracy each observer needs to determine his or her effective wavelength for a range of spectral types.

14.2 The Instrument

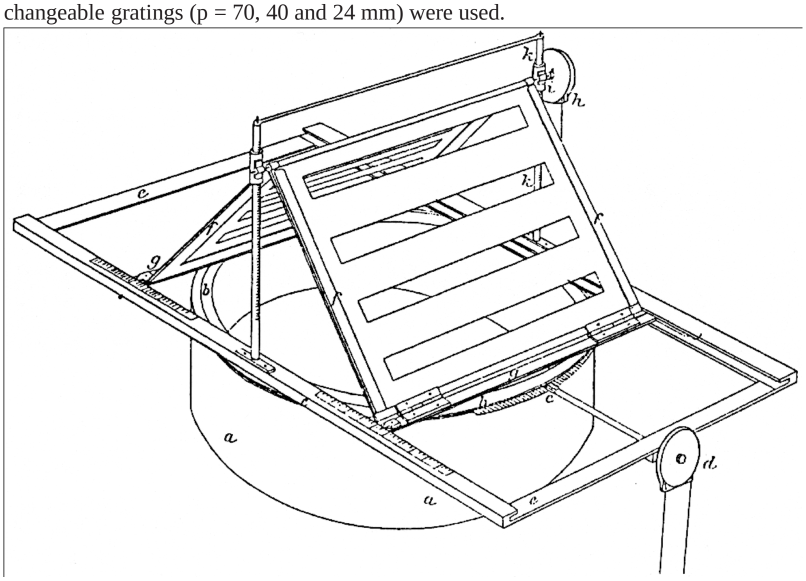
As the separation range which can be measured, depends on the value of p, to measure all double stars in the range of a given telescope would require quite a number of gratings.

In practice though there is a way to overcome this problem. With a few gratings and some elementary geometry, the basic method can be considerably refined. In this case, a set of four gratings is used with slit distances of 10, 20, 30 and 40 mm. The widths of the bars separating the slits are normally half the slit distance.

14.3 The measurements

The star images and their satellites can be arranged in particular configurations depending on the orientation of the grating. Provided that the pattern is carefully arranged, the grating slit distance and the grating orientation, together with a little trigonometry can deliver quite accurate results for both the PA and separation of the double star being observed. Several star patterns have been proposed by previous observers (1) and the method has been continuously refined. It was extensively and successfully used and described by French and English double star observers in the 1980's (2, 3, 4).

Fig. 14.2 The Schwarzschild adjustable diffraction micrometer used in 1895. Three pairs of interchangeable gratings (p = 70, 40 and 24 mm) were used.



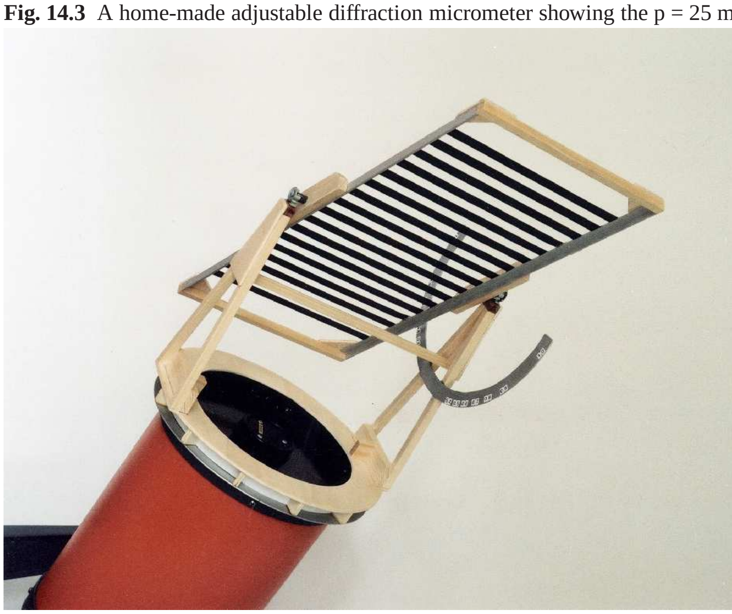
Obviously the most convenient method would be a grating with adjustable slit distances, thus minimizing the number of gratings and rendering trigonometric calculations superfluous. Such an instrument had already been proposed by Karl Schwarzschild in 1895 (5). He used three sets of different gratings which he arranged in front of the objective glass of a 10-inch refractor like a roof with rising and descending ridge as shown in Fig. 14.2 . In this way he could produce variable slit distances, as seen from infinity. The instrument was adjustable by ropes from the eyepiece end.

Lawrence Richardson (6) described a simpler, home-made adjustable interferometer consisting of a flat grating frame which could be tilted in front of a small 4.5-inch refractor. This was the construction which served as model for the one described here, an easy-to-build, adjustable grating micrometer. It is made of aluminium, board and plywood and is designed for use on the popular 20-cm Schmidt-Cassegrain telescopes. Needless to say the principle of the instrument can also be used on other types of telescopes.

14.4 Construction

This micrometer consists basically of two parts: (1) a rectangular grating frame in front of the telescope objective or corrector lens, which can be tilted with respect to the optical axis and (2) a flange for mounting this frame with its support onto the objective end of the tube. This flange allows the device at the same time to rotate and its orientation can be read on a 360-degree dial (Fig. 14.3). The apparent slit distance is varied by inclining the frame which has to be large enough to cover the telescope aperture even when tilted. On the other hand, the frame should not be larger than absolutely necessary in order to keep the instrument size within reasonable limits. Here one has to compromise: as an example, the construction shown in Fig. 14.3 works with a 230 $\times$ 520 mm frame and the maximum useful tilt is about 65 degrees. The projected slit distance varies as the cosine of the angle of inclination. Therefore the frame-tilt graduation is not in degrees but directly in corresponding cosine values, thus simplifying the reductions.

Fig. 14.3 A home-made adjustable diffraction micrometer showing the p = 25 mm grating.



For effective diffraction at least 3 to 4 slits should be used in front of the objective so for a 20-cm telescope the largest slits will be about 25 mm wide and arranged 50 mm apart. According to the diffraction formula such a slit distance can thus be used for measuring double star separations from 5.5 to about 2.5 arc seconds. For smaller separations larger telescope apertures are essential. If the 20-cm telescope is to be used for double star separations of up to 10 arc seconds, say, two grating frames with 50 mm and 25 mm slit distances will do. The smaller grating - used for larger separations - will, when inclined at 65 degrees, produces a projected slit distance of 10.6 mm, which corresponds to about 11 arc seconds separation. If wider separations are to be measured a third frame with smaller slit width could be made. However, the stability of the narrow grating strips could become a limiting factor.

In order to get reliable measures, grating frames should be precisely made. The slits and bars should be accurately parallel to each other and also to the tilting axis. Broad aluminium bars of width 25 mm or alternatively 12.5 mm and 1.0 mm thick are glued onto a frame made of 10 mm aluminium angle and wood. The tilting axis consists of small pivots on each frame side which turn in clamps as shown in Fig. 14.4. These clamps allow a frame-exchange within seconds and they also produce just the right friction for the frame to tilt very smoothly.

Fig. 14.4 Metal clamps serve as bearings for the grating frames and allow a quick exchange of frames. Note the cosine scale for reading the frame inclination.

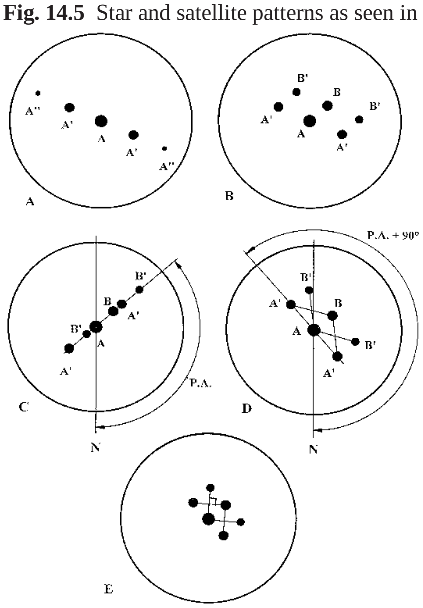
Two lightweight side frames support the two grating frame bearings which in turn are fixed to the bottom flange as shown in the photographs. This wooden flange is provided with a cardboard collar on its back, which fits onto the end of the telescope tube. The fit should be tight enough to keep the micrometer properly in place even at low elevations but at the same time not too tight to prevent it being turned around its axis. A collar which is slightly too large is preferable because the desired clearance can then be fixed by inserting some shims of paper or felt. At the collar bottom a 1.5 mm aluminium ring is glued to its rim. This aluminium ring carries a 360-degree scale or dial and contributes at the same time considerably to the micrometer's stability. This scale, which indicates the double star position angle, is read by a properly set pointer or marking on the telescope tube. Having an outer diameter of 270 mm the scale allows precise reading but if desired a vernier scale could be added. To establish the dial's zero-point the grating slits have to be exactly parallel to the telescope declination axis. In this position the satellite images of a star are aligned North-South. The weight of the micrometer should be kept as low as possible in order not to disturb the balance of the telescope. The instrument shown in the photographs weighs not more than 500 g.

14.5 Observing

To make an observation the micrometer is fitted to an equatorially mounted, correctly aligned, and carefully collimated telescope. The 50 mm or the 25 mm grating frame is mounted, depending on the expected separation of the pair to be measured and as high a magnification as possible should be used, preferably 400x or more. The first step is to align the two star components and their satellite images exactly by rotating the whole micrometer (Fig. 14.5c). This is called the alignment method and it gives position angles with great precision. Only when the stars and satellites appear properly aligned in a straight line is the position angle read on the 360-degree dial. At this point it should be noted in which quadrant the fainter star lies in case a correction of 180 degrees needs to be made to the measured position angle. Then the micrometer is rotated exactly 90 degrees further and a configuration as shown in Fig. 14.5d will be seen. Now it is time to start tilting the grating frame. This is an easy procedure because when observing with a short 20-cm Schmidt-Cassegrain telescope the grating frame can still be directly reached and operated from the eyepiece end. Great care and judgement is necessary to determine the frame‘s inclination which produces the correct star configuration. There are two alternative patterns: perfect squares or, perfectly right-angled crosses as shown in Fig. 14.5e. The idea behind this is, of course, to set the angular distance of the satellite images exactly equal to the double star separation. The mode of operation quickly becomes second nature with the observer and, of course, the larger the series of settings and readings the more reliable the result. In order to compensate for instrument inaccuracies and to increase the precision further, the frame should be swung to both sides and readings on either side on the cosine scale should be made. Furthermore as the satellite images appear on either sides of the stars, two squares or crosses are shown, hence both of them should be judged. As a final verification, the angles A'BA' as well as B'AB' can be checked for perfect orthogonality. Incidentally if a diagonal prism is used the ”cross” pattern can be arranged vertically or horizontally for better judgement simply by turning the diagonal. Experience shows that judgement seems to tire quickly so decisions have to be made quickly and alternate glances with either eye yields a clearer result instead of staring for too long at the patterns. Only when perfect accord is obtained is the tilt angle cosine read directly from the scale. To get the final value for “p” the grating’s nominal spacing, i.e. 50 or 25 mm, is multiplied by this cosine. Now the diffraction formula can be used to calculate the double star separation, rho.

It is not necessary to use the ”cross” configuration in Fig. 14.5e. By swinging the frame, the aligned stars and satellites as shown in Fig. 14.5c could for instance be brought directly to exactly equal distances A’- B’- A - B - A’ -B’ which makes the next step, the instrument’s 90° position angle turn, superfluous. Depending on the chosen, lined up star and satellite arrangement, the cosine reading will then need a correction before using the value in the formula. In the described example it has obviously to be divided by two. Other alignments - with corresponding correction factors - are possible and thereby the range of the micrometer could be extended considerably. Occasionally, when crowded stars and satellites are lined up in this way, it is perhaps not easy to distinguish stars and satellites. Hence the ‘cross’ configuration as described earlier and shown in Fig. 14.5e is preferred, as it works without this added difficulty.

Fig. 14.5 Star and satellite patterns as seen in the eyepiece.



14.6 Disadvantages

Diffraction micrometers have one drawback. As the grating consists of bars and slits with the same width, only 50% of the incident light from the double star will reach the telescope optics. Of this, about 50residual light will end up in the zero-order images resulting in a total loss of 1.5 magnitudes compared with the unobstructed telescope. Another 20% goes into each of the first order images, the rest being lost in the additional satellites. Because of these losses the combination of a 20-cm telescope and a diffraction micrometer will allow observations of double stars as faint as about magnitude 7.0 to 7.5 with components which do not differ too much in brightness.

The diffraction micrometer formula includes the factor λ , the wavelength of light. As the observation is made visually the satellite's exact distance from the primary star depends on the observer's own wavelength sensitivity but also on the stars‘ colours. The observer's most sensitive wavelength which should be used in the formula has to be established by comparisons with pairs with accurately known separations. A normal figure for λ to start with might be 5650 Å, or 0.000565 mm if p in the formula is in millimetres. This corresponds approximately with the effective wavelength of a white, class A spectral type star.

14.7 Accuracy

What about the accuracy of a home-made adjustable diffraction micrometer and what kind of factors will influence a result?

First of all, as with all double star measures, the better the seeing conditions the better the accuracy. Trying to get results during poor seeing periods will end up in frustration. Good seeing allows high magnifications, which in turn produce large and easy-to-judge star configurations. Then, to obtain accurate results, a series of say 10 to 12 grating adjustments and readings should be made for a pair; and before the final mean values are determined, such series should even be repeated on consecutive nights. Most crucial for the accuracy of the result is certainly the precise judgement of square and right angle combinations between stars and satellites in the field of view. Equally bright pairs are obviously easier to judge and are thus likely to be more accurate than very unequal pairs.

Also the separation has an influence on accuracy; the closer a pair the higher the magnification needed for a clear interpretation of its satellite arrangement. But the higher the magnification the sooner the seeing can become a limiting factor with its potential negative influence on accuracy. Nevertheless, diffraction micrometer results are surprisingly reliable. Position angles can be obtained with mean errors of 1 deg. and this is good enough to proceed to the next step, the separation measurement. Based on a large number of observations made during acceptable seeing, it can be concluded that for a typical double star the angular separation can be determined typically with a mean error of about $\pm 2\%$, but considerably more precise results have often been obtained. Indoor tests under perfect seeing conditions with artificial double stars have shown that still more can be expected from this instrument.

What this means numerically can be shown using two typical examples: for Castor's two bright components (magnitudes 1.9 and 2.9), which in the year 2000 were $3''.8$ apart, an accuracy of better than $0''.1$ was obtained. In the case of a faint and wide pair, such as STF 1529 in Leo, consisting of components of magnitude 6.6 and 7.4 and separation $9''.5$, the separation was determined with an error of less than $0''.2$.

Not only are the precision of the construction and careful tuning of star configurations important for the result's reliability, the assumed star wavelengths will also, as the formula predicts, directly influence the accuracy. Catalogues such as the Bright Star Catalogue can supply information about the spectral classes of brighter stars of which Table 14.1 is a small subset. From Richardson's papers, these classes correspond approximately to the following visual wavelengths.

B0: 5620 Å A0: 5640 Å F0: 5660 Å
G0: 5680 Å K0: 5710 Å M0: 5760 Å

The wavelengths between classes A - F, F - G or G - K do not differ considerably, each step being roughly 0.5%. Hence one might be tempted at first sight to ignore stars' spectral classes altogether, but why ignore useful information when these figures will help to improve the result's accuracy? And here comes a warning: initial diffraction micrometer results with these wavelength figures may perhaps show some strange systematic variations. These can be due to the observer's eye sensitivity or individual interpretation of the star and satellite configurations. Such variations can, as soon as enough experience has been accumulated, be eliminated by personal correction factors.

Is it possible to use the measuring method in reverse to try to calculate and determine the effective observed wavelengths of double stars when their separations and position angles are accurately known from catalogues? With a large database of catalogue data for PA and separations, double star wavelengths can be determined with similar accuracy to separation. Such wavelength determinations will reveal possible hardware weaknesses, and the overall accuracy can be improved accordingly.

The delicacy of spectral class distinction can also be demonstrated by observing a double star whose components have very different colours. A suitable example is Σ470, consisting of stars of spectral classes G8 and A2 stars and similar brightnesses (magnitudes 4.5 and 5.7). When the images are arranged in the standard "cross" configuration, slightly larger satellite distances for the yellow G8 primary, when compared with the white A2 secondary's satellites, are expected. But even when the two stars, as in this case differ by as much as two spectral classes, it is difficult to detect the slight difference of the first order distances because the two satellite separations still differ by only 1% or so. Hence, for calculating the separation of a double star with components of different spectral class, the mean wavelength of the two stars can safely be used.

Table 14.1 Pairs with known spectral types near the celestial equator

RA 2000 Dec	Pair	Epoch	PA(°)	Sep(″)	Va	Vb	Sp. Types	Name
01137+0735	STF100	2000	63	23.2	5.21	6.44	A7IV+F7V	ζ Psc
01535+1918	STF180	1999	0	7.7	3.88	3.93	A1+B9V	γ Ari
03543-0257	STF470	1991	348	6.9	4.46	5.65	G8III+A2V	32 Eri
05350-0600	STF747	1994	224	35.8	4.78	5.67	B0.5V+B1V	
05351+0956	STF738	1997	44	4.3	3.39	5.35	O8+B0.5V	λ Ori
05353-0523	STF748	1995	96	21.4	4.98	6.71	O7+B0.5V	θ^1 Ori
06090+0230	STF855	1991	114	29.2	5.70	6.93	A3V+A0V	
06238+0436	STF900	1991	29	12.4	4.39	6.72	A5IV+F5V	ε Mon
08555-0758	STF1295	2000	4	4.1	6.07	6.32	A2+A7	17 Hya
12413-1301	STF1669	1998	313	5.2	5.17	5.19	F5V+F5V	
13134-1850	SHJ151	1991	33	5.4	6.26	6.76	A0V+A1V	54 Vir
14226-0746	STF1833	1995	174	6.1	6.82	6.84	G0V+G0V	
14234+0827	STF1835	1996	194	6.0	4.86	6.86	A0V+F2V	
14241+1115	STF1838	1997	336	9.4	6.76	6.94	F8V+G1V	
14514+1906	STF1888	2002	316	6.5	4.54	6.81	G8V+K5V	ξ Boo
15075+0914	STF1910	1997	212	4.0	6.72	6.95	G2V+G3V	
15387-0847	STF1962	1991	189	11.8	6.45	6.56	F8V+F8V	
18562+0412	STF2417	1993	103	22.6	4.62	4.98	A5V+A5V	θ Ser
19546-0814	STF2594	1991	170	35.6	5.70	6.49	B7Vn+B8V	57 Aql
20299-1835	SHJ324	1991	239	21.9	5.94	6.74	A3Vn+A7V	o Cap
20467+1607	STF2727	2000	266	9.2	4.27	5.15	K1IV+F7V	γ Del
23460-1841	H II 24	1993	135	6.8	5.28	6.28	A9IV+F2V	107 Aqr

Is the diffraction micrometer then even capable of earmarking individual spectral classes? For this purpose, an alternative method, which involves measuring the value of z directly by timing several transits of circumpolar stars can give values of z for a typical grating to an accuracy of about 0.3%. It is necessary to have an eyepiece fitted with a vertical crosswire in order to time the passage of the two first-order images across the centre of the field (1) Table 14.2 gives a short list of bright circumpolar stars with a range of spectral types which are suitable for this purpose.

14.8 Conclusions

Diffraction micrometers have not only a long and interesting history, they can deliver precise measurements at little cost. If they are made with adjustable slit distances they are easy to use because of easily identifiable star patterns involving a minimum of calculation work. They are therefore ideally suited for amateur observers who want to build a micrometer for their own use.

Table 14.2 A short list of bright circumpolar stars suitable for determining the value of z

Star	RA2000	Dec2000	V	B-V	Spectrum
HR 285	01 08 44.7	+86 15 25	4.25	1.21	K2II-III
alpha UMi	02 31 48.7	+89 15 51	2.02	0.60	F7:Ib-II
HR 2609	07 40 30.5	+87 01 12	5.07	1.63	M2IIIab
delta UMi	17 32 12.9	+86 35 11	4.36	0.02	A1Vn
HR 8546	22 13 10.6	+86 06 29	5.27	-0.03	B9.5Vn
HR 8748	22 54 24.8	+84 20 46	4.71	1.43	K4III
zeta Oct	08 56 41.1	-85 39 47	5.42	0.31	A8-9IV
iota Oct	12 54 58.6	-85 07 24	5.46	1.02	K0III
delta Oct	14 26 54.9	-83 40 04	4.32	1.31	K2III
chi Oct	18 54 46.9	-87 36 21	5.28	1.28	K3III
sigma Oct	21 08 46.2	-88 57 23	5.47	0.27	F0III
tau Oct	23 28 03.7	-87 28 56	5.49	1.27	K2III

14.9 References

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Chapter 15
CCD Camera Observations

Bob Buchheim

15.1 Introduction

One night late in 1918, astronomer W. Milburn, observing the region of Cassiopeia from Reverend Espin's observatory in Tow Law (England), discovered a hitherto unrecorded double star. He reported it to Rev. Espin, who measured the pair using his 24-inch reflector: the fainter star was 6.0 arc-seconds from the primary, at position angle 162.4 degrees (i.e. the fainter star was south-by-southeast from the primary). Some time later, it was recognized that the astrograph of the Vatican Observatory had taken an image of the same star-field a dozen years earlier, in late 1906. At that earlier epoch, the fainter star had been separated from the brighter one by only 4.8 arc-sec, at position angle 186.2 degrees (i.e. almost due south. Were these stars a binary pair, or were they just two unrelated stars sailing past each other? Some additional measurements might have begun to answer this question. If the secondary star was following a curved path, that would be a clue of orbital motion; if it followed a straight-line path, that would be a clue that these are just two stars passing in the night. Unfortunately, nobody took the trouble to re-examine this pair for almost a century, until the 2MASS astrometric/photometric survey recorded it in late 1998. After almost another decade, this amateur astronomer took some CCD images of the field in 2007, and added another data point on the star's trajectory, as shown in Figure 1

There is a tantalizing hint of a curved path, but it will require additional measurements, spanning another century, to have convincing evidence of what (if any) relationship exists between these two stars.

There are several lessons hidden in this story. First, the value of measuring double stars has not diminished ? there are a variety of stellar studies that can make good use of the properties of binary stars whose orbits are well-determined. And it would be just as valuable to know for certain that these two stars are not related, that they are traveling on their own independent paths which merely appear from our perspective to be along the same line-of-sight, but which are in fact at vastly different distances from us. Second, orbital periods can be very long, so that the necessary

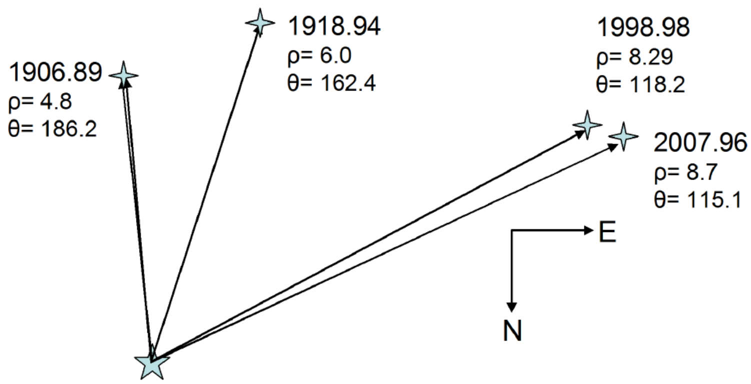

Fig. 15.1 Historic measures of MLB 102

measurements are likely to span an interval that is longer than the life of any single astronomer. Rev. Espin died in 1934, and while I am (as of this writing) still up and kicking, I will be long gone before this orbit is closed - if it is, indeed, an orbit. Third, if a pair goes unobserved for a long interval of time, the record of their motion during that lost interval cannot be recovered. In the example of MLB 102, with only four data points, there is an infinity of possible ellipses, each of which connect the data to within measurement uncertainties. There are a great many such pairs whose positions haven't been measured in over 20 years, and so there is an ongoing need for measurement of visual double stars. The amateur astronomer's CCD imaging system has all of the attributes desired in a precision astrometric measuring device. Using the CCD to measure double stars is one way for the amateur astronomer to become a ?backyard scientist? whose data is shared with the astronomical research community.

If you have taken any number of CCD astro-images, you have doubtless noticed some close pairs on some of your images, and may have wondered how to measure their separation and position angle. You may also have wondered if those measurements have scientific value. As it turns out, it isn't too difficult to make the necessary measurements with quite nice accuracy, and yes, indeed, there may be value in your measurements.

Even better, there are readily-available software packages that will work through virtually all of the math for you, so that the separation and position angle of a double star can be determined with just a few mouse-clicks on the image.

This project of measuring double stars is real science. It must be done with quite fine precision, and it requires both skill in imaging and rigor in analysis. Hence, you may have some trepidation about undertaking it. Here's my advice: skim through this chapter, take images of a few double stars which have well-attested parameters, analyze your images, and compare your results to the ?well-attested? parameters. You will probably find a few problems, or discover that you made a few mistakes; and you'll also see that the mistakes are easily corrected. With this experience, your second session will probably be quite successful, and you can then begin measuring and reporting double star parameters for the benefit of current and future astronomers.

15.2 Principles of CCD Double Star Astrometry

Consider the CCD image shown in Figure 2. Near the center is a fairly well-separated double star (SKF-10). How do we determine the separation and the position angle of this pair, from such an image?

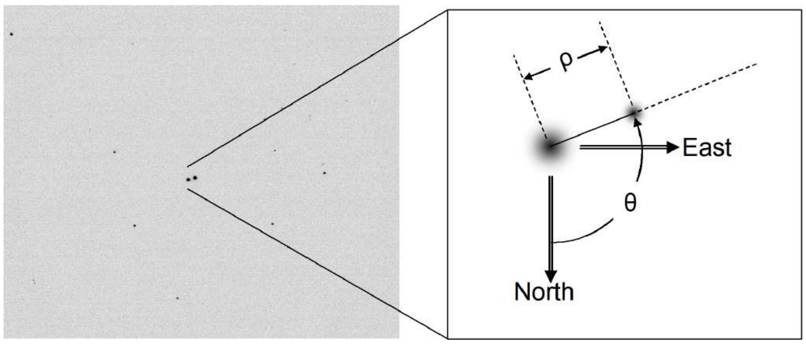

Fig. 15.2 CCD Image of the pair SKF-10

The geometrical idea is pretty simple – draw a line from the primary star to the secondary star, measure the length of the line (ρ), and measure the angle (θ) between that line and the direction pointing north. This begs the questions of how you know the image scale (how many arc-sec per pixel) and the image orientation (which directions are 'north' and 'east' on your image). CCD double-star observers use image-processing and analysis software to make the necessary calculations and reductions. There are two ways that these software packages handle the necessary computations: 'astrometric fitting' and 'plate scale/image orientation'. The next two sections describe the concept and procedure for each of these methods.

15.2.1 The 'Astrometric Fitting' Method

Suppose that you could determine the RA, Dec coordinates of every star in your image. This is the essence of the 'astrometric fitting' method of image calibration. The idea is to find a transformation from pixel coordinates to RA, Dec coordinates, such as (in matrix notation):

$$\begin{bmatrix} RA \\ Dec \end{bmatrix} = \begin{bmatrix} T \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

The transformation matrix [T] describes the scale, position, and orientation of the celestial coordinate frame relative to the pixel coordinate frame. The process of determining the transformation from (x,y) to (RA, Dec) is often referred to as 'matching' the image to an astrometric star catalog. The mathematical details need not concern us here, because you won't have to do any of it yourself.

15.2.1.1 'Matching' the image to a star catalog

If you use a CCD, you also have software for viewing, reducing, and analyzing the images - programs such as MAXIMDL, CCDSOFT, AIP4WIN, and ASTROART are widely used. Each of these packages can match the image to a star catalog, so that you can retrieve the RA, Dec of each star in the image simply by clicking on it. Deep in the software code, these programs are determining the transformation matrix as part of their matching routine. Astrometric-analysis software packages such as MPO Canopus or Astrometrica also match your image to a star catalog with just a couple of mouse-clicks, enabling you to display the calculated RA, Dec coordinates of any star in the image

An example, using Software Bisque's CCDSOFT, is shown in Figure 3. With CCDSoft and TheSky both open, the command 'Research/InsertWCS' conducts a match between the image and the star catalog in THESKY, and reports some information about the results of the matching. Although the exact command and screen shots differ, all of the programs mentioned do this task in very similar ways.

15.2.1.2 Measuring unknown pairs

Once the image has been 'matched', you can click on any star in the image and the program will display the calculated RA, Dec coordinates of the star. So, click on the two stars of your pair, and jot down their coordinates. Given the RA, Dec of two stars, the separation and position angle are calculated by:

$$\rho = \sqrt{(\Delta_\alpha . cos\delta_1)^2 + (\delta_2 - \delta_1)^2} radians$$

$$\Theta = tan^{-1} \frac{\Delta_\alpha . cos\delta}{\delta_2 - \delta_1} radians$$

where δ_1, δ_2, are the declination of the primary and secondary stars, respectively and α_1, α_2 are the right ascension of the primary and secondary stars, respectively, and $\delta\alpha = \alpha_2 - \alpha_1$ is the difference of RA, and all of these angles are expressed in radians.

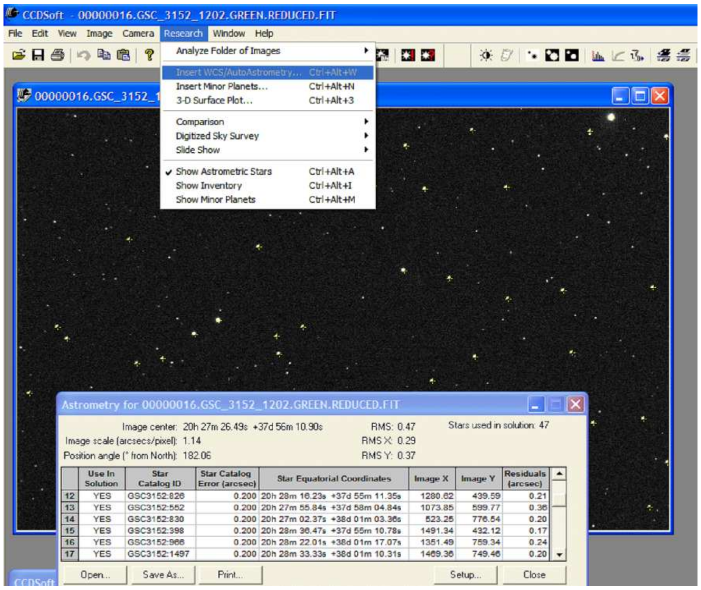

Fig. 15.3 Example of Astrometric Fitting (using CCDSoft and TheSky)

The calculated position angle, , must be resolved to the correct quadrant in order to yield the astronomical position angle (?, measured from celestial north, toward celestial east):

sign of	sign of	quadrant	position angle
+	+	I	$\theta = \Theta$
+	-	II	$\theta = \pi + \Theta$
-	+	III	$\theta = \pi + \Theta$
-	-	IV	$\theta = 2\pi + \Theta$

These calculations can readily be put into a spreadsheet, so that all you need to do is enter the RA, Dec of each of the two stars, and the spreadsheet will calculate ρ and θ. An Excel spreadsheet that does this is available at [insert Springer website].

The MPO Canopus and AIP4Win software will do all of these calculations for you. With their 'double star' utilities, you select the primary star and set it as the reference, then select the secondary star, and the separation and position angle are displayed - no calculating required!

15.2.2 *The 'Plate Scale and Image Orientation' Method*

Any software than can read and display your CCD image will be able to show the pixel coordinates (x,y) of your stars. With that information, you can find ? and ? in pixel coordinates. In order to translate them from the pixel coordinate frame to the celestial coordinate frame, you need to find the image scale, and the orientation of the celestial coordinate frame in the image.

The ‘image scale’ expresses the magnification of the image, in arc-seconds per pixel. It is denoted by E. It is sometimes referred to as the ‘plate scale’, in honor of the glass plates that were used before CCD imagers took over the task of recording images at professional observatories. If the distance between two stars is R pixels, then their separation in arc-seconds is just:

$$*\rho = E.R \qquad arc - secs \tag{15.0}$$

*

The ‘image orientation’ expresses the rotation of the CCD image relative to the celestial coordinate frame. It is denoted by Δ. This is the angle between celestial North and the X- or Y- axis of the image.

The image scale is primarily a function of telescope focal length and the physical size of the CCD pixels, although it can also be affected by focus changes and other secondary effects. Image orientation is primarily determined by the rotation of the CCD camera in the telescope’s focus tube, and of the way the image is read, stored, and analyzed, although again there are secondary effects that can affect the orientation angle. Therefore, these two parameters (E and Δ) must be determined for each observing session – which I’ll refer to as ‘calibrating’ the images for that observing session. If the camera is not moved, these parameters will change little (if at all) from night to night; but it is a necessary discipline to check the calibration for each imaging session to ensure the best accuracy of your measurements. Fortunately, the calibration requires no more than a couple of images, so it doesn’t impose a troubling loss of observing time. The reduction of the calibration images also isn’t too time-consuming.

15.2.2.1 Determining the image scale (E) and image orientation (Δ)

The image scale and orientation are determined by analyzing images of one or more ‘calibration’ pairs, whose separation and position angle are accurately known. Then, using the values of E and ? determined from these ‘calibration’ pairs, it is a simple matter to translate images of other pairs from pixel coordinates (x,y) into separation and position angle (ρ, θ).

The concept of this method is illustrated in Figure 4. In order to use this method you need to know the approximate orientation of the CCD image (i.e. roughly which way is ‘N’ and which way is ‘E’ on the image). Position angle is always measured from North toward East, so you need to know whether that means ?clockwise? or ?counterclockwise? on your image. There are two ways to determine this: ?eyeball matching? your image to a chart from a planetarium program, or using a star trail image. For most imaging setups it is common practice to compare your image to the chart on your planetarium program, to (for example) properly frame the image and adjust any pointing errors. Most planetarium programs will display a compass rose showing the cardinal directions (N, E, S, W). From that, you can easily see (and record in your notebook) the image orientation.

If for some reason 'eyeball matching' to your star chart isn't practical (perhaps a very narrow FOV, or a sparse field where there aren?t enough stars to compare the image to chart), then you can make a star trail image. Open the shutter, wait a couple of seconds and then stop the clock drive. The 'blotch' on the star trail (i.e. the deeper exposure before the clock-drive was stopped) shows the Eastward (starting) location of the star trail. Midway through the exposure, nudge the telescope a bit toward the South. The resulting 'bump' in the star-trail will point Northward on your CCD image. In the example shown in Figure 4, ? increases counterclockwise, but depending on your setup ? the type of telescope, the presence of a star-diagonal, etc. ? the opposite may be true for your images.

Now, make an image of a 'calibration pair'– a pair of stars whose separation and position angle are accurately known. From this image, we will determine the plate scale (E) and image orientation angle (Δ). Determine the position of each star, in pixel coordinates:

$$*\mathrm{P}rimarystar = (x_1, y_1) \qquad \mathrm{S}econdarystar = (x_2, y_2) \tag{15.0}$$

*

If the known separation of the calibration pair is ρ_{cal} (in arc-sec), the plate scale is calculated by:

$$E = \frac{\rho_{cal}}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}} \qquad {''}\ perpixel$$

The angle to the secondary star in the pixel coordinate frame will be called β_{cal}, defined by

$$tan(\beta_{cal}) = \frac{(y_2 - y_1)}{(x_2 - x_1)} \quad \mathrm{so}\ that \quad \beta_{cal} = tan^{-1}\frac{(y_2 - y_1)}{(x_2 - x_1)}$$

The image orientation angle (Δ) is the rotation of the image relative to the celestial coordinate system - you can think of it as the angle between the X-Y axes of the CCD pixel array and the RA-Dec axes of the sky. We know that the position angle of the calibration pair is θ_{cal} (relative to the celestial frame). By reference to the example in Figure 4, you can see that

$$\theta_{cal} = \beta_{cal} - \Delta + N\pi \quad so\ \ that \quad \Delta = \beta_{cal} - \theta_{cal} + N\pi$$

The term Nπ indicates that, because of the quadrant ambiguity in the arc-tan function, you will need to examine the graph of your image, and adjust the calculated value of

$$tan^{-1}(\Delta_y/\Delta_x)$$

to put it into the correct quadrant, with N= 0, 1, or 2 depending on the quadrant.

By the way, you can use astrometric fitting as a way to determine the image scale and orientation, or to check your calculations. Look back at Figure 3: The information that was displayed about the astrometric fit of the image included the image scale (E = 1″.14 /pixel) and image orientation angle (Δ = 182°.06). Most (but not all) astrometric fitting programs report this information, which you can either use "as-is", or use as a check on your calculations from the 'calibration' pairs.

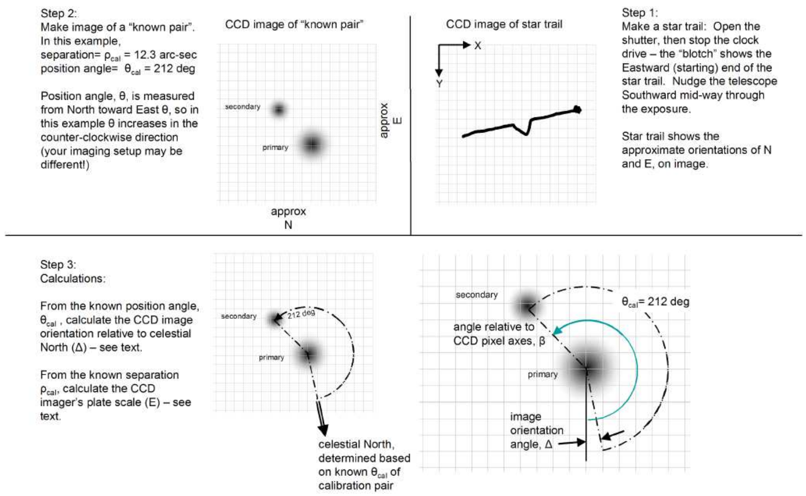

Fig. 15.4 Using a 'Calibration pair' to determine image orientation

15.2.2.2 Measuring unknown pairs

Now that you know E and Δ, you can determine the separation and position angle of any pair on any image. Just determine the pixel coordinates of the two stars,

primary star centroid = (x_1, y_1); secondary star centroid = (x_2, y_2)

and apply the following equations (in pixel coordinates):

$$\rho = e.\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}\,pixels$$

$$\theta = tan_{-1}\frac{(y_2 - y_1)}{(x_2 - x_1)} - \Delta + n\pi radians$$

radians Eq. 7

Always make a little graph (like Figure 4-d) to confirm that your calculation of the inverse tangent is in the correct quadrant. Depending on the orientation of celestial axes relative to the CCD X and Y axes, you may need to adjust the results by ±180 degrees (Nπ radians) to put it in the correct quadrant.

This method of calibrating your images is nicely automated in the software package REDUC, which does all of the math and turns this method into a very quick and easy procedure.

15.3 Special-purpose software

Your normal CCD image-processing software can do a fine job of analyzing most of your double-star images so that you can use Eq. 1 and Eq. 2, or Eq. 6 and Eq. 7, to determine the separation (ρ) and position angle (θ). CCDSoft+ TheSky, MaximDL, AIP4Win, and AstroArt are all quite capable programs in this regard. AIP4Win even includes a distance-measurement tool that determines the separation and position angle of any two stars in the 'matched' image.

If you catch the double-star bug, you may find that the additional features of special-purpose software applications are useful to you. Three such programs that I am most familiar with are Astrometrica, MPO Canopus, and REDUC.

Astrometrica, by Herb Raab, is a general-purpose astrometry program. Some of the unique features of Astrometrica that are useful for double-star measurements include:

- With an image open, a one-click command will match the image to a reference star catalog. With the matched image, you can click on any object, and a window opens showing you the (calculated) RA, Dec, magnitude, and some information about the quality of the fit. The RA, Dec from each star in a pair can then be entered (by you) into a spreadsheet, to use equations Eq.1 and Eq.2 to calculate ρ, θ.
- Astrometrica will open and astrometrically analyze a batch of images with a single command.
- It supports a wide array of modern astrometric catalogs. The catalogs can be stored on your local hard disk, or accessed over the internet. Large, modern astrometric catalogs such as UCAC3 and USNO-B1.0 can be loaded onto your local hard drive (e.g. 7.9 GB for the 100,766,420 objects in the UCAC3, with positions accurate to about 0.02 arc-sec and including proper motion). The internet-access feature is quite seamless, and enables you to access a variety of astrometric catalogs, including the 100 GB NOMAD catalog
- It is the only program I am aware of that allows you to select higher-order plate constants. Most programs use first-order plate constants, which in effect mean that they assume that the image scale and orientation are constant across the image. This is usually a quite good assumption, but if you have a wide-FOV system, or field curvature or any of a variety of possible aberrations, the use of higher-order plate constants may be helpful.
- Astrometrica uses a form of PSF-fitting in order to determine the location of stars. For bright, isolated stars, there is no noticeable difference between this PSF approach and the intensity-centroid approach used by most other programs.

However, for closely-spaced pairs, where the PSFs begin to touch, Astrometrica's algorithm seems to do a better job of separately locating the two stars.

Astrometrica is distributed by internet download. It can be purchased at `www.astrometrica.at`. As of this writing, the license costs *e*25. Astrometrica is 'shareware?, so you can download and use it for 100 days to confirm that it meets your needs, before paying the license fee.

MPO Canopus, by Brian Warner, is a full-feature astrometric and photometric program. Some of the unique features of MPO Canopus that are useful for double-star measurements include:

- MPO Canopus includes a clever double-star utility. One click on each star in the matched image, and the double-star utility calculates, displays, and reports the separation and position angle of the pair (i.e. no need to work through Eq. 1 and Eq.2)
- Correction of the position angle for precession, to the epoch of observation. (See the discussion below on precession). The preferred reporting of position angle is based on the pole and equator of the epoch of the date of observation, which MPO Canopus will do automatically. Other ?astrometric fitting? algorithms inherently report the position angle based on the pole and equator of the epoch of their underlying catalogs. This is usually a small effect, unless the pair being measured is very close to the celestial pole (e.g. Dec 85 degrees),
- Use of any of several astrometric catalogs, including USNO-A1, USNO-A2, UCAC-3, and the proprietary MPOSC3 astrometric/photometric catalog.
- A convenient utility for automatically measuring a batch of images, collating the measurements, and creating a report form.
- MPO Canopus has the ability to sum images in 32-bit format, which expands the numerical dynamic range of the calculations.

MPO Canopus is distributed on DVD (which includes the program and the MPO photometric and astrometric Star Catalog with 300M stars). It can be purchased at `www.minorplanetobserver.com`. As of this writing, the licensed DVD costs $65. A multi-seat educational license is available for the same price.

REDUC was developed specifically for double-star measurements by Florent Losse. It implements and streamlines the use of the ?image scale and image orientation? method. Some of the unique features of REDUC are:

- REDUC has routines that will calculate your plate scale (arc-sec/pixel) and field rotation based on one or more calibration pairs.
- REDUC can use either a calibration pair alone, or a calibration pair plus a star trail image to define the image orientation.
- It offers 'two-click' measurement of the position of each star, with automatic calculation of the separation and position angle of the pair. Manual-entry or ?calibration pair? determination of plate scale (arc-sec/pixel) can be used.
- It does a fine job of accepting a batch of image files of a double star, automatically reducing all of them, and creating a report with each image's results, plus the average and standard deviation of the batch.

- Its image-evaluation utility sorts a batch of images in order of quality
- Automatic calculation of ρ, θ as each image/pair is measured
- Automatic report-preparation
- REDUC includes a ‘Surface’ routine, that implements a version of PSF image modelling to accurately measure very close pairs, whose PSFs overlap significantly. This is the only program that I’m aware of that can reliably and accurately reduce pairs that are so closely spaced that their images overlap noticeably.
- Its magnifying and re-sampling algorithm can help separate closely-spaced pairs for measurement.
- REDUC is freeware! This very sophisticated package is available free, upon request from the author.

Go to the author’s website at www.astrosurf.com/hfosaf/, and follow the instructions to request the software download.

15.4 Mathematical Considerations

The idea of determining separation and position angle is an easy concept ? you probably worked this problem in your high school Trigonometry class. That really is all that is required to make a double-star measurement using your CCD image, and as we?ve seen, there are several choices of software packages that will do most of the arithmetic for you. So, it isn’t absolutely necessary that you know what is going on inside those software packages. However, in order to understand the rationale behind some of the advice coming in the sections about the imaging equipment, procedures, and pitfalls, it helps to peek through the curtain of the mathematical methods.

15.4.1 Position of Stellar Image - Intensity Centroid and PSF match

A star’s image is not a mathematical point. How do we define the ?location? of the star? How do we measure the location? And, can we determine the star’s location more accurately than ± 1 pixel? It is worthwhile to look closely at the CCD image of a single star while considering these questions.

15.4.1.1 The Point Spread Function

When your telescope focuses on a single star it forms an intensity distribution on the focal plane (the CCD chip), called the Point Spread Function (PSF). Ideally this is a smoothly peaked brightness blur, which represents the convolution of the telescope's diffraction and aberration characteristics, the atmospheric effects, and any 'accidental' defects such as tracking error, as shown in Figure 5. The CCD chip then does three things to this smooth PSF: it spatially integrates the brightness over each individual pixel, it samples the pixels, and it adds several types of random noise. The net result of this is a discretely-sampled, noisy version of the intensity distribution. The exact nature of this sampled PSF depends on the size of the pixels, and where the star is registered on the pixel array.

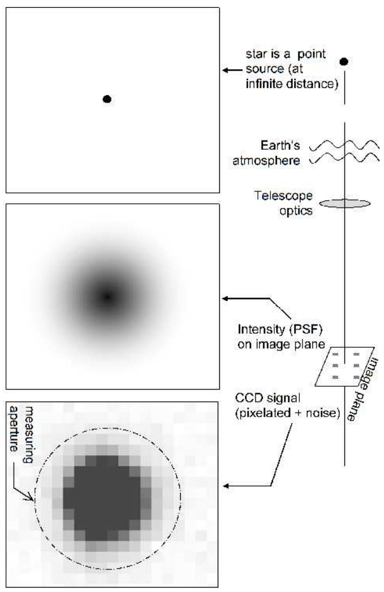

Fig. 15.5 The CCD's image of a star – the Point Spread Function (PSF) – is a blurred, discretely sampled intensity distribution, with random noise added.

The width of the PSF is frequently described by its full-width-at-half-maximum (FWHM). The FWHM may be expressed in either pixels or arc-seconds, depending on the context.

An important feature of the sampled PSF is that even in the absence of noise, the center of the brightest pixel may not be the best estimate of the location of the center of the star's underlying Intensity PSF. An illustrative example of this is shown in Figure 6, for a case of 5μ pixels, and the star's 'true' center falling 2μ to the right of the 'center' pixel. Simply assuming that the brightest pixel is the position of the star would be in error by nearly half a pixel width. We can do much better than that!

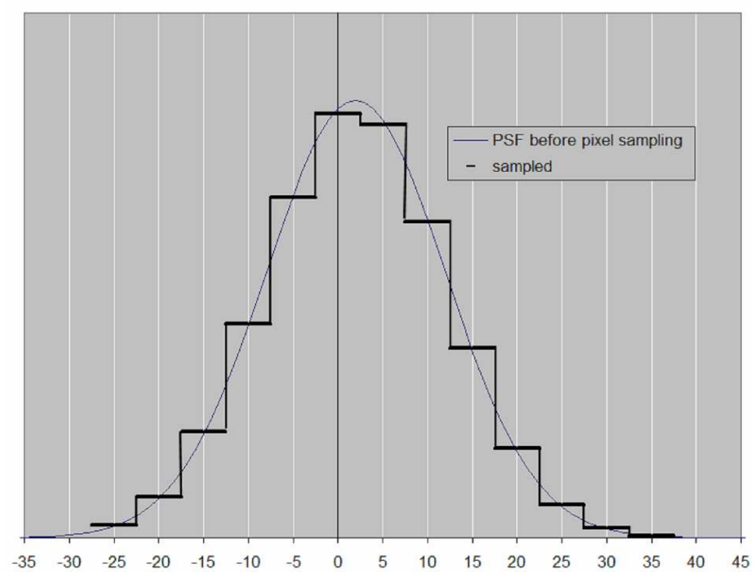

Fig. 15.6 The center of the 'brightest pixel' is not the best estimate of the star's position

15.4.1.2 Intensity Centroid and PSF fitting

The best estimate of the location of the star's image is usually taken to be the intensity centroid of the sampled point spread function. If we use pixel coordinates (x, y), the coordinates of the intensity centroid are:

$$X_c = \frac{\sum x.I(x,y)}{\sum I(x,y)} \qquad and \qquad Y_c = \frac{\sum y.I(x,y)}{\sum I(x,y)}$$

The summations extend over the 'measuring aperture' - the small portion of the CCD image that encompasses the star. The measuring aperture may be square or circular depending on the software that you use ? either is quite acceptable. The measuring aperture should normally be selected to be large enough to capture all of the star's light, but not so large that it captures a great deal of background sky, nor any other nearby stars. A typical starting choice is a measuring aperture that is about 2 to 3 times the FWHM of your star images.

There are two important features of these equations for the centroid.

If the pixels are too large compared to the size of the optical PSF, then the star's location can be lost inside the large pixel. Suppose that the pixels are so large that only a single pixel has light on it. This is the situation illustrated in Figure 7b. The equations then tell us the location of that one-and-only illuminated pixel: the best estimate of the location of the star is the centroid of that one-and-only pixel. In this situation, there is a limit to the accuracy of your position determination ? you can't know the star's location more accurately than ± 0.5 pixel.

As the pixels become smaller (compared with the optical PSF), then the sampled PSF becomes an increasingly more accurate representation of the optical PSF (as in Figiure 7a, and Figure 6). The equations can then find the location of the centroid of the star to a small fraction of a pixel. For a typical backyard CCD imaging set-up, with a scale of about 1 arc-sec/pixel, you should be able to achieve position accuracy of a tenth of an arc-second, which is quite remarkable accuracy!

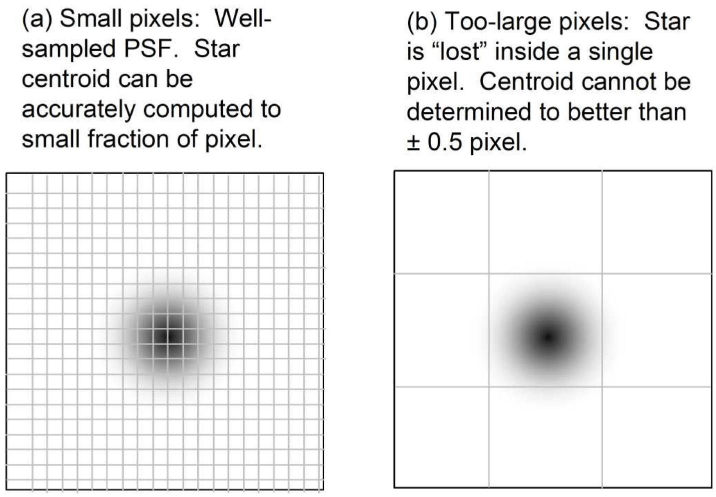

Fig. 15.7 (a) With small-enough pixels ($\sim$ 0.25 FWHM) the star's centroid can be calculated to a small fraction of a pixel. (b) With too-large pixels, the star can be 'lost' inside a single pixel

An alternative definition of the 'location' of the stellar image, called 'PSF fitting', is sometimes used. In particular, the program Astrometrica uses this approach. The idea is to construct a mathematical/theoretical PSF, and find the best fit (position, intensity) between the mathematical PSF and the actual image. Call the model PSF

$$PSF(x,y;x_0,y_0) = F[(x-x_0),(y-y_0),A_0,w_0]$$

where the center position of the model star is (x_0, y_0), its intensity is A0, and the 'spread' of the PSF is described by the parameter w0. If the actual intensity distribution of the star image is I(x,y), then the estimate of the position of the star is the position (x_0, y_0) that minimizes the sum-square error:

$$\chi^2 = \sum[PSF(x,y;x_0,y_0) - I(x,y)]^2$$

where the summation extends over all pixels in the measuring aperture of the image.

As long as the image has a high signal-to-noise ratio, is well-formed, well-sampled, and not affected by neighboring stars, the 'centroid' and 'PSF fit' will give the same the same result for the position of the star.

15.4.2 Position of Double-Star Images

The image of a close pair of stars is just the sum of their two PSF's. Figure 8a shows the intensity profile of a widely-spaced pair of unequal magnitudes, displaying two distinct peaks. In this situation, it is practical to determine the position of each star by calculating its centroid, because there is a reasonably clear boundary between the stars.

As the separation becomes smaller (Figure 8b), the stars become so close together that is isn't possible to measure their individual centroids. With no clear boundary between the stars, their individual PSFs have blended into a single blur, and wherever you place the measuring aperture for star #2, it will inevitably include some of the light coming from star #1, which of course invalidates the centroid calculation. The greater the magnitude difference, the wider the pair must be in order to cleanly distinguish the two stars. Note that the situation can easily result in there not being two distinct peaks in the combined intensity distribution. Instead of a secondary 'peak', the fainter star may be represented by only a bulge in the side of the PSF.

How close is ?too close to measure?? The point at which such an overlapping intensity profile becomes ?too close to measure? depends on a variety of factors. The larger the delta-magnitude, the more widely separated the stars must be to be measurable. The higher the SNR, the more distinct the fainter star will be. If the width of the star's PSF becomes smaller (e.g. due to a night of better seeing), then closer pairs can be measured. In general, once the stars become closer than about 2X FWHM, they are difficult to separate. Closer than about 2X FWHM, the centroid algorithm is likely to be problematic because there is no longer a clear separation between the stars? PSFs.

The ?PSF fitting? algorithm can usually derive accurate positions for stars that are somewhat closer together than the ?centroid? algorithm can handle. Still, at separation less than 2X FWHM it is likley to also have a hard time separating the stars. One nice feature in this situation is that the magnified view of the ?calculated? and ?image? PSF (in Astrometrica) gives you a good indication of the adequacy of the fit. If the stars are too close to measure it will be obvious on the display.

15.4.2.1 PSF Image Modeling

When the stars in a pair are so close that their PSFs overlap significantly, any method that relies on separately determining the position of each star will be problematic. As shown in Figure 8, because of the overlap it isn't 0meaningful to search for a boundary where one star ends and the other begins; instead, one star's PSF simply fades into the other. Worse, the centroid of the fainter star may not correspond to a locally brightest pixel. In fact, there might not even be a ?locally brightest? pixel. And any error in finding the centroid of the stars will translate into a quite large error in position angle.

One solution to this is to use a mathematical approach that is an extension of PSF fitting. Instead of finding/measuring the position of each star individually, you make a mathematical model of two overlapping PSFs, and find the separation/position angle that minimizes the difference between your math model and the actual image intensity distribution. Much closer pairs ? down to about 1X FWHM ? can be measured with such a ?PSF image modeling? algorithm (assuming well-sampled images, good SNR, and not-too-large magnitude difference).

Call the actual image intensity distribution

$$I_IMAGE(x,y)$$

and the mathematical model of the PSF of a single star centered at (x_1, y_1)

$$PSF(x,y) = f[(x-x_1),(y-y_1),w_x,w_y]$$

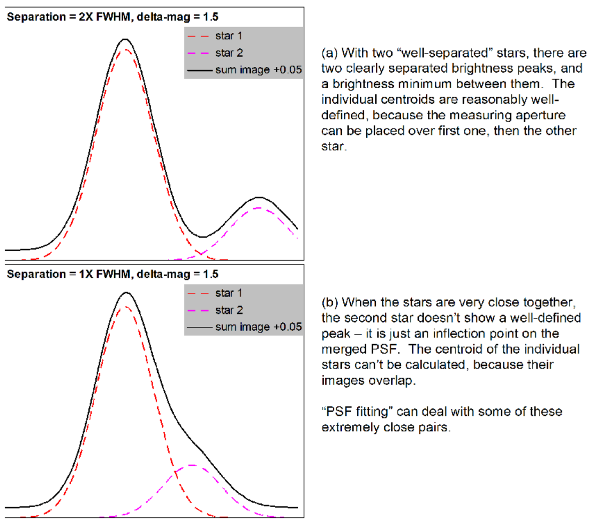

Fig. 15.8 'Too close' pairs do not display distinctly separate images ? two stars become one merged image.

The function f can be any well-behaved function that reasonably matches the shape of the PSF ? different authors have used Gaussian, Moffat, and polynomial functions. The mathematical model of two stars, centered at (x1, y1) and (x2, y2) respectively, is just the sum of their two PSFs, scaled by their relative brightness. Call this the ?model? intensity distribution:

$$I_{MODEL} = A_1.f[(x-x_1),(y-y_1),w_x,w_y] + A_2.f[(x-x_2),(y-y_2),w_x,w_y]$$

where A_1 and A_2 are the relative brightness of the stars, and w_x, w_y describe the width of the PSF function (e.g. the σ if a Gaussian PSF model is used). The squared-difference between the image and the model is:

$$\chi_2 = \sum[I_{IMAGE} - I_{MODEL}]^2$$

The challenge is then to search for the values of x_1, y_1, x_2, y_2, w_x, w_y, A_1 and A_2 that minimizes χ^2, and to compare I_{IMAGE} to I_{MODEL} to confirm that the model is, indeed, a good match to the actual image.

This approach is quite a bit more work than using 'astrometric fitting' or 'image scale and orientation', with their user-friendly commercial programs, but it does permits the accurate measurement of pairs that would otherwise be too close to deal with. An example of a very close pair (separation slightly less than 1X FWHM) is shown in Figure 9.

I am not aware of any commercial software that implements this method, although the 'Surface? routing in REDUC appears to be a very similar formulation. The necessary calculations can be programmed into a spreadsheet. Most modern spreadsheet programs (e.g. Microsoft Excel) include iterative solvers that will search for the parameter values that give the best fit between model and image.

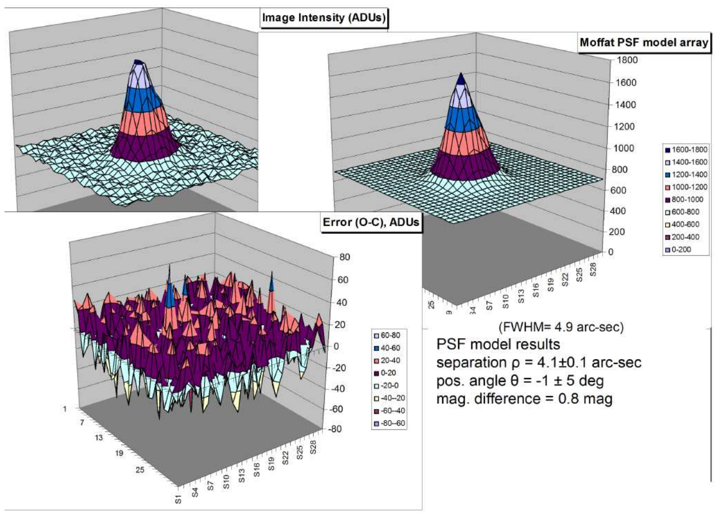

Fig. 15.9 Example of the capability of PSF-modeling to measure a very close pair on a CCD image

15.5 Considerations Related to Atmospheric Effects

We live at the bottom of an ocean of air, and the atmosphere causes a variety of distortions and degradations to starlight before that light enters our telescopes. Whereas photometrists prize the clearest nights, and deep-sky astro-imagers are happiest under the darkest sky, the condition of most value to double-star measurements is stability: no atmospheric turbulence to blur the star images. Measurement of double stars is not noticeably affected by haze, light pollution, or moonlight, so this is one project that can be pursed on those full-moon nights where deep sky observing or photometry are not practical. And if conditions are poor one night, you can simply try again ? unlike comets and asteroids the double stars will be available in the same place for a repeat attempt on a better night!

The air scatters and absorbs starlight, so that in general any star will appear fainter and redder when it is near the horizon than it does when it is at the zenith. This effect is very important for photometry and spectroscopy, and as a result astronomers have developed a variety of ways to determine (and compensate for) this effect. It does not have a direct adverse impact on double star ρ, θ measurement, but you may have to consider it if you are measuring the magnitude/color difference between the two stars.

The air also bends starlight, and this bending can (roughly) be thought of as three effects: refraction, turbulence, and dispersion.

15.5.1 Refraction

Refraction refers to the fact that a light ray is ?bent? by the density gradient of the atmosphere (dense near the surface, tenuous at high altitudes). The closer a star is to the horizon, the greater the displacement between its ?observed? position and its ?true? position. This effect is illustrated in Figure 10. Refraction always makes the star appear to be higher in the sky than it would be in the absence of Earth's atmosphere; and the change of refraction angle as the star moves away from the zenith is quite spectacular. It is this effect that causes the ?oval-shaped? Sun when it sets over a low horizon.

Happily, the effect of refraction on measurement of double stars is quite modest. Since both stars of a double-star pair are very close to each other, they are refracted almost identically, so that their measured separation angle is nearly unaffected. The magnitude of the difference in refraction between the two stars in a pair (assumed to be aligned vertically, which is a worst-case assumption) is shown in Figure 10c. When the double star is fairly high in the sky, (say zenith distance less than 60 degrees, i.e. 30 degrees or more above the horizon) you can usually neglect this effect, since it is much smaller than the probable accuracy of your measurements

15.5.2 Turbulence ('seeing?)

Atmospheric turbulence makes stars ?twinkle?, and moves the star images around randomly. For most situations, the CCD exposure is long enough that these random motions are time-averaged into a smooth blur (the Point-Spread Function), and the center of the blur is a good estimate of the position of the star on the image plane. Very short exposures (such as those used in ?lucky imaging?, as discussed in Chapter xx) can 'freeze' the turbulent motion, so that the star's image is becomes a nearly-perfect diffraction-limited spot; but still, the turbulence will cause that spot to move about, so that each short-exposure image places the star-spot in a slightly different location on the image plane. The image may be nearly diffraction-limited, but it still bounces about a bit from image to image.

Will two adjacent stars 'bounce about' in exactly the same way, or will the atmospheric turbulence cause them bounce toward or away from each other, thereby changing the separation and/or position angle? Theoretical studies show that bounce toward or away from each other. The magnitude of the RMS separation change depends on the details of the atmospheric conditions at the time of observation, but most models give pretty similar predictions. The trends are intuitive: more widely separated the stars are (so that each star 'sees' turbulence that is less correlated with what its neighbor 'sees'), and the shorter the exposure time (so that there is less time-averaging of the turbulence-induced motions), the greater the relative motion will be. However, for the situations likely to be encountered by amateur astronomers and backyard scientists, it does not have a significant amplitude. The turbulence-induced RMS change in separation is shown as a function of exposure time in Figure 11, for an 8-inch (20-cm) telescope, and pairs separated by 30 arc-sec and 150-arc-sec. When the exposure is longer than a few seconds, the RMS differential position fluctuation caused by atmospheric turbulence is less than 0.1 arc-sec – a tiny fraction of the nominal separation of any measurable pair.

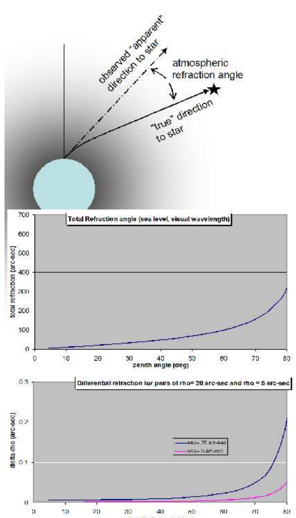

Fig. 15.10 Total refraction and differential Refraction.

So, be aware of this effect, but don't worry about it unless you are using extremely short exposures. If you must use very short exposures, taking and measuring multiple images and averaging the resulting measurements has the same ?time averaging? effect that longer exposures would give, reducing the effective amplitude of this effect.

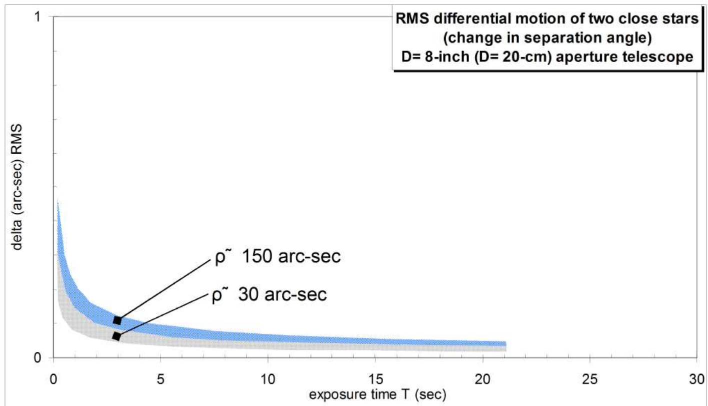

Fig. 15.11 Differential image motion caused by atmospheric turbulence is only noticeably on very short exposure images

15.5.3 Dispersion

Differential chromatic refraction: The third property of the atmosphere ? dispersion ? is that it bends blue light more than it does red light (because the refractive index of air is higher in the blue than it is in the red). Each star is thus spread out into a little spectrum, with blue light deflected toward the zenith and red light toward the horizon.

The theoretical amount of differential chromatic refraction as a function of wavelength, for an observatory at sea level, is illustrated in Figure 12. This graph shows the angular dispersion between the indicated wavelengths (colors), and a wavelength of ?=0.5 ?m that was arbitrarily chosen as the ?reference? wavelength. Note that the dispersion increases dramatically as the viewing direction approaches the horizon. (The dispersion effect becomes smaller for higher elevation observing sites, but the advice to avoid viewing too close to the horizon ? i.e. below zenith angles of about 60 degrees ? still holds).

These curves show that different colors of light are refracted slightly differently, and that the effect increases dramatically at large zenith angles. Suppose that you were dealing with two stars, one of which was quite blue, radiating only at 0.4 ?m, and another star that was quite red, radiating only at 0.6 ?m. Further assume that your sensor has uniform sensitivity, regardless of wavelength, and that there is no turbulence in the atmosphere, so that the star images are perfectly small (all of these assumptions are, of course, quite unrealistic, but they help to visualize the situation). In this idealized case, at 50 degrees zenith angle, the blue star is moved by 1 arc-sec (toward the zenith) and the red star by -0.5 arc-sec (away from the zenith), so that their apparent (observed) separation may be between 0.5 arc-sec smaller to 1.5 arc-sec greater than ?truth?, depending on which star is higher in the sky. That's a significant effect, compared to the 0.1 arc-sec accuracy that you?re striving for!

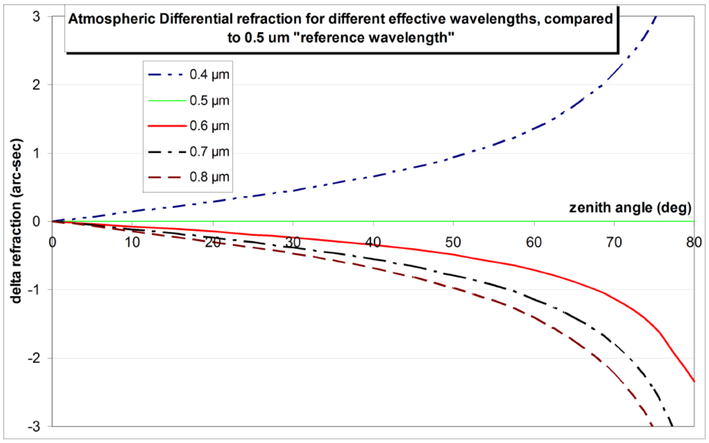

Fig. 15.12 Dispersion (Differential Chromatic Refraction) can be a noticeable effect for sightlines that are close to the horizon.

In a more realistic situation, the stars radiate in all colors, but the blue star radiates more blue than red, and the red star radiates more red than blue, so the centroids of their spectra are differentially moved, a bit. The CCD sensor is more sensitive to some colors than others (e.g. an unfiltered CCD tends to be more sensitive to red than blue light), and this spectral sensitivity curve tends to reduce the impact of differential refraction of starlight. The narrower the CCD's spectral response, the smaller the effect of differential refraction.

This atmospheric effect argues strongly for imaging the pairs when they are as high in the sky as practical. In general, ?too close? to the horizon means lower than 30 degrees elevation. There is no drawback, and might be some benefit, to using a spectral filter, especially if you are forced to image at large zenith angle, or if you know that the colors of the stars in the pair are quite different. A Red or Infrared filter is preferred (since dn/d? is smaller at longer wavelengths).

As a practical matter, this is not likely to have a significant effect on your double-star measures, as long as you observe near the zenith. If you have any reason to suspect that the stars are of significantly different color, and you can?t observe them high in the sky, then using a narrow spectral filter will reduce the effect of dispersion on your images and measurements.

15.6 Considerations Related to Taking and Processing CCD Images

Almost any amateur telescope/CCD combination can be used to make useful double star measurements, so if you already have an imaging system, I encourage you to press it into the service of double-star science! The following guidelines may help you adjust your setup for the best possible accuracy; or help you select which of your imagers+telescopes will make the best combination. In what follows, I will assume that you have already confirmed that you have an acceptable imaging setup: the telescope is well-collimated and can be accurately aimed at a target, the mount tracks accurately and smoothly (possibly with the help of an autoguider), the focus can be smoothly and accurately adjusted, and the resolution of the images is limited by either seeing or diffraction.

15.6.1 Image Sampling and Pixel Size

One significant difference between double star measurement and more artistic astro-imaging is that double star measurement requires well-sampled images, in which the pixels are smaller than the stars PSF. (Refer back to the discussion about determining the star's location). The requirement that the pixels be significantly smaller than the size of a star's image is an aspect of the Nyquist sampling principle: the PSF must be ?well sampled?. The pixels should be two or three times smaller than the FWHM in order to get a good representation of the shape of the PSF. Figuring that most amateur observing locations present atmospheric seeing of 1 to 3 arc-sec (FWHM), the general rule is to strive for pixels that subtend between 0.3 to 1 arc-second. Smaller is generally better, and anything larger than 2 arc-sec is likely to be problematic.

If the physical size of the pixels in your CCD is D ?m, and your focal length is F millimeters, then the angular size of your pixels is

$$\phi = 206.3\frac{D}{F}$$

arc-sec

Most commercial CCDs (and digital SLR cameras) have physical pixels sizes in the range 5 μ to 24 μ. All other things being equal, double-star measurements suggest selecting a CCD with pixels at the small end of this range; but if you already have a CCD imager with larger pixels, that is not really a problem ? it just means that you should arrange to use a long-enough focal length (perhaps by adding a Barlow lens to your optical train). Achieving a pixel angular size of 1 arc-sec, implies focal length in the range of 1000 mm (for 5 μ pixels) to 5000 mm (for 24 μ pixels). These are not extravagant requirements. A 4-inch f/10 telescope (or an 8-inch scope at f/5) provides F $\sim$ 1016 m, and a 10-inch f/10 telescope provides F 2540 mm. Add a 2X

Barlow to that 10-inch f/10 'scope, and you'll have F $\sim$ 5080 mm, which will give 1 arc-sec angular pixels even with physical pixels of 24 μ.

A rule-of-thumb is that star images should be round. If your star images appear to be 'square?, then your images are undersampled, and your pixel's angular size is too large.

There is, of course, a downside to smaller pixels. The light of the star is spread across many pixels, so the signal-to-noise ratio (SNR) on each pixel is lower. If the star's signal is too small (i.e. the SNR is not very high), then the noise can ?pull? the centroid noticeably away from the noise-free location of the star's centroid; and since the noise is a random process you don?t know on any given image what it has done. This is rarely a serious problem for double-star imaging. The normal practice is to (1) take long enough exposures to get a high SNR ($>$50:1) which will result in small positional error from the residual noise, and (2) take a handful of images, and average the calculated centroids, to ?average down? the positional noise, reducing the uncertainty in the position.

Most modern commercial CCDs have square pixels. If you work through the equations for finding the star's centroids (Eq. 1 and Eq. 2), and their separation and position angle, you will see that they are based on the assumption of square pixels. This was strictly a matter of convenience ?most of the data reduction software can handle rectangular pixels transparently.

The equation for pixel angular size above implicitly assumed a monochrome imager, which is normally the preferred choice for scientific applications. Single-shot color imagers (including DSLRs) have a color mask in front of the sensor chip, that segregates pixels into three patterns. One pattern is sensitive to red light, another pattern (staggered from the first) is sensitive to green light, and a third pattern (staggered again) is sensitive to blue light. In order to have a well-sampled point spread function in this situation, the star's PSF must touch at least 3 pixels of the same color (in both directions). The centroid calculations should be done using only a single color, extracted from the merged image. Most image processing programs that can handle single-shot color CCD (and DSLR) images can separate the colors into single-color image files, so that you can do the astrometric analysis on a single color.

15.6.2 Polar alignment

Errors in polar alignment of your mount lead to residual field rotation as your telescope is pointed to different regions of the sky. The risk, magnitude and impact of this effect depends on your setup, the location of the target pair, and on the procedure you use for measuring the pairs. If your telescope is permanently mounted and has been accurately drift-aligned, then the risk is probably low. If you use a portable setup and rougher polar alignment, the risk of such field rotation as you point to different parts of the sky is higher. The equation for field rotation (rotation of the parallactic angle) is given in Chapter xx. For the case of equatorial-mounted telescopes, a small error in polar alignment causes rapid field rotation when pointed near the celestial pole, and pretty modest field rotation rates if you stay more than 10 – 15 degrees away from the pole.

This field rotation is of no consequence if you are using the ?astrometric fitting? method, since the transformation from (x,y) to (RA, Dec) will account for the actual field orientation of the image.

Field rotation can affect your measures of position angle if you are using the ?image scale and image orientation? method. Figure 13 illustrates the impact of a 1-degree error in polar alignment. In this graph, the image orientation is set to zero for any point on the meridian (Hour Angle = 0). At any line of constant declination, the image rotates as you point away from the meridian. As shown, the image rotation is quite small if you are viewing far from the pole, but as declination becomes large (e.g. the Dec= 72° and Dec= 85°.5 curves), the image rotation also becomes large.

How much image rotation can a polar misalignment cause? Using Figure 13, here is an example. Suppose your polar alignment error is 1 degree, and that your target pair is at declination 72 degrees, very close to the celestial pole. Further, assume that your ?calibration pair? is exactly at the meridian when you image it, but then you slew through 3 hours of RA in order to aim at your target pair. The field will rotate (as a result of the slew + polar misalignment) by 2.4 degrees, and so your calculated position angle would be in error by ± 2.4 degrees (depending on whether your target pair was 3 hours to the east or the west of the meridian). Granted, this is an extreme example, but the point is that gross polar alignment errors can corrupt your determination of image orientation (Δ). Beware of this if you are measuring pairs that are close to the celestial pole.

Your first preventive action in this regard is to carefully polar-align your mount. If you have any question about the accuracy of your polar alignment, you should select calibration pairs that are reasonably close in the sky to the fields that you are measuring, to minimize field rotation between the ?target? and ?calibration? fields. (This is another good reason to consider using ’synythetic? calibration pairs. Constructing ‘synthetic calibration pairs’ from field stars in the image of your target pair avoids any concern regarding image rotation).

15.6.3 Exposure - Signal-to-Noise Ratio

The collection of photons onto a single pixel of your CCD imager is a random process, governed by the statistics of photon arrival, the efficiency with which the chip converts photons into electrons (its quantum efficiency), and the random creation of electrons by thermal and other effects in the sensor. If a series of identical images are made, and you carefully examine the same pixel in each image, the recorded ADU won?t be the same number on each image ? it will vary because of these (unavoidable) factors. Call the average ADU value S, the ’signal?. The RMS variation of the ADU value, N, is the ?noise?, and the signal-to-noise ratio is SNR= S/N. If all

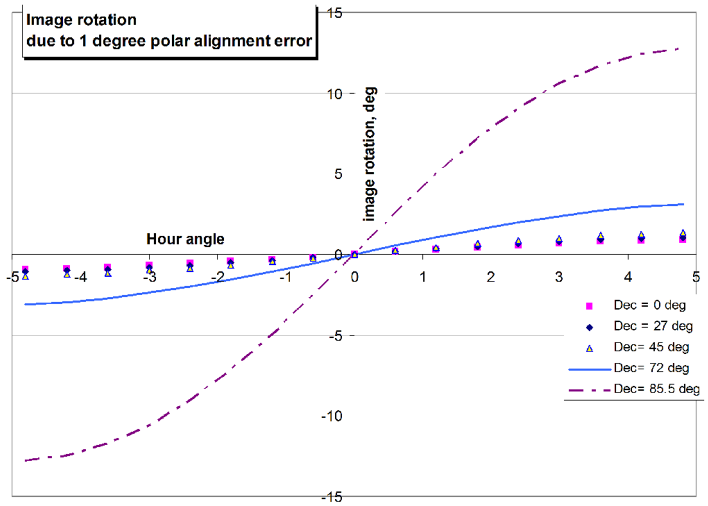

Fig. 15.13 Inadequate polar alignment causes noticeable field rotation at high declinations.

other noise sources are eliminated, the SNR is set by the statistics of photon arrival, in which case it will be:

$$SNR = \sqrt{g.ADU}$$

where g is the 'gain' of the imager (photoelectrons per ADU). Of course, additional noise sources will reduce the SNR.

The accuracy with which the position of a star can be determined is fundamentally limited by the SNR. One estimate of the achievable astrometric accuracy is

$$\sigma_{ast} = \frac{FWHM}{2.36 \times SNR}$$

arcseconds

where: FWHM is the full-width-at-half-maximum if the star's PSF (in arcseconds) and SNRpeak is the signal-to-noise ratio of the brightest pixel in the star's image.

If your observing site's seeing conditions result in stellar images with FWHM $\sim$ 3 arc-sec, and you are striving for measurement accuracy of 0.05 arc-sec, this equation implies a minimum requirement for SNRpeak $\sim$ 26. Since there are other noise sources in the image, striving for double this is wise, and it is usually no problem to achieve SNR $\sim$ 50 with modest exposure duration. (With g $\sim$ 2.3, this implies a signal of S $\sim$ 1000 ADU)

15.6.4 *Exposure: Dynamic Range*

Pairs with large magnitude difference present a special challenge to CCD users, because of the limited dynamic range of the sensor.

Most modern commercial CCD imagers use 16-bit output (ADU values from 0 to 65,535), although there are doubtless some 12-bit units still in use (which can display ADU values from 0 to 4095). The 16 (or 12) bits create a hard limit on the dynamic range that the sensor can record. Suppose, for example, the noise (from photon, dark current, and read noise) is 50 ADU RMS. Suppose further that the primary and secondary stars differ by 6 magnitudes (i.e. intensity ratio = I1/I2 = 10?M/2.5 = 251). If we select an exposure that puts the peak pixel of the primary star at 50,000 ADU ? near the saturation level of a 16-bit imager ? then the peak pixel of the secondary star will be only 50,000/251 200 ADU. We have a very high SNR1= 50,000/50 = 1000:1 on the primary star, but only SNR2=200/50= 4:1 on the secondary star. Position measurement of the secondary star at this low SNR would probably have an unacceptably l arge uncertainty. If the magnitude difference were 7 magnitudes (intensity ratio = I1/I2 = $10^{M/2.5}$ = 631), then secondary star would be umeasurable (maybe even undetectable, with peak ADU = 50,000/631 = 79 ADU, and SNR 1.6 in the image). Thus, the limited dynamic range of the imager presents a significant constraint in dealing with pairs with large delta-magnitude. Either the primary star will be saturated (and hence its position not accurately measurable), or else the secondary star will be buried in noise (and hence not accurately measurable).

If your CCD has ‘anti-blooming gates’ (ABG), then its linear dynamic range may be reduced. The output of these sensors tends to become non-linear above about] 50% of the full-well depth (i.e. about 32,000 ADU in our example), which aggravates the dynamic range problem.

Large delta-mag systems are a real challenge for CCD measurement! If you want to venture into this territory, the most impressive approach that I?ve seen is that invented by James A. Daley. He makes a small partially-transmitting ‘occulting mask’ by cutting a small strip from a mylar solar filter. This is placed at the focal plane of the telescope, and a lens assembly is used to re-image the (partially occulted) focal plane onto the CCD chip. The target pair can then be placed in the FOV so that the light of the primary star passes through the partial-occulting mask (and is thereby diminished), but the secondary is not occulted. This dramatically reduces the dynamic range of the image, and makes accurate measurement possible. An excellent description of this innovative approach, and its application to large delta-mag systems, is described in a series of articles in JDSO by Mr. Daley – see, for example JDSO v. 3 no. 4 (Fall 2007) p. 159.

A simpler approach - not as robust as Daley’s, but helpful in cases of moderately large delta-mag ? is to convert the individual 16-bit images to 32-bit images (several software programs will do this, including MaximDL and MPO Canopus), and then sum a couple of dozen images together. Summing n images improves the SNR by a factor of $\sqrt{(n)}$ (i.e. summing 25 images will improve the SNR by a factor of 5). In our example of the $\Delta_m \sim 6$ mag pair, this would increase the SNR of the fainter star to a useable SNR 20. Since the summation is done in 32-bit arithmetic, the computation can handle over 2 billion ADU per pixel ? a virtually unlimited dynamic range. If you use this approach to dealing with a high-delta-mag pair, you should test your software and calculations on a few summed images of easily measured pairs, to be sure that you understand how your software handles the summation of 32-bit images.

15.6.5 Filters

Unfiltered images collect the maximum amount of starlight, hence maximize SNR for a given exposure. So, many reported double-star measures are based on unfiltered imagery.

You may choose to use a filter to minimize atmospheric dispersion effects and also to minimize the effect of chromatic aberration in your telescope (more likely to be of concern if you are using a short-focus refractor). This will probably require longer exposure, but may well improve the overall accuracy in your measurements. Particularly if you are imaging far from the zenith (say zenith angle $>$ 50 degrees), it may be wise to use a red filter (either the ?R? from an RGB imaging filter set, or the ?R? or ?I? band filter from a photometric BVRI set) to minimize differential chromatic refraction.

Another reason to consider using filters is the case where the primary star is substantially brighter than the secondary. If the two stars have different colors, you may be able to reduce the delta-magnitude between them by judicious selection of a filter. For example, if the primary is red and secondary is blue, try a blue filter: it will dim the primary, and have less effect on the secondary. This may make it possible to get a better SNR on the secondary without saturating the primary.

15.6.6 Autoguiding

This depends very much on the accuracy of your mount's tracking, and the exposure that you are using. Try a few experiments to determine the tracking accuracy of your mount without guiding ? what fraction ?good? images do you get at different exposures? Then decide whether to autoguide based on the exposure that you?re using to capture your target images.

15.6.7 Science images

Do not ever rely on a single image. There are too many things that can go wrong! If an image has an accidental defect within the measuring aperture (such as a cosmic-ray hit or a ?hot? or ?cold? pixel) then the calculated position of one or both stars may be erroneous. This risk can be minimized by using multiple images, and allowing the pair to drift a bit between images (so that they don?t sit on the same hot pixel, for example).

Take 6 to 12 images of each pair, so that the range of results will provide a basis for estimating the consistency of the measurement, and to allow for tossing out the occasional obviously flawed image.

Because many WDS pairs are fairly bright, it is often quite feasible to make a great many exposures in a short observing session on a given target. Take advantage of this: some software programs contain utilities that will automatically sort through your images, selecting the ?best? ones so that you can then analyze just the dozen best images.

15.6.8 File formats

Most CCDs give you several options for the format of the stored image data. The astronomical standard is FITS ? an uncompressed file format whose header can accept certain useful information from the camera and the telescope (e.g. time and exposure duration of image, RA-Dec and Alt-Az of telescope pointing). This is the preferred format, rather than proprietary or compressed file formats. In particular, compressed image formats such as JPEG may impair routine image processing steps that may be useful in double-star observations. All of the commonly-used CCD image-processing programs can read and manipulate FITS format images.

In the case of DSLR cameras, the choice of file format is usually JPEG or ?Raw? (or both). The ?Raw? format is recommended, because it contains almost-unprocessed image data which can be manipulated (e.g. summing multiple images) if necessary. Many popular CCD image processing software packages can read and manipulate Nikon and Canon ‘raw’ image files.

15.6.9 Flats and Darks

Yes, take them and use them! The effects of dust donuts and dark current on double star measurement are usually much less serious than they are on CCD photometry, but nevertheless it is good practice to reduce your images with bias, dark, and flat fields so that you are using the best possible image data in your measurements.

You may be able to imagine worst-case scenarios in which failure to reduce your images can have bad impact on your double star measures. For example, suppose that one of the stars is sitting exactly on the edge of a dust-donut, so that the right half of the PSF is unaffected, but the left half of the PSF is substantially dimmed by the edge of the ‘donut’. The calculated intensity centroid will be pushed to the right, compared to the ‘true’ position of the star. Or, suppose that a hot pixel is lying in the left wing of the PSF: the intensity centroid will be pulled toward the left, compared to the ‘true’ position of the star. Granted, these are pretty unlikely scenarios. But we?re striving for very high accuracy (say, a tenth of a pixel), and there is no convenient way to notice that your image is corrupted in this way, so it is safer to do the routine CCD image reductions before analyzing your images.

Always save both your raw and reduced images, just in case you discover later that there was something wrong with your darks or flats. This may never happen to you, but I have been known to inadvertently reduce a 1-minute exposure with a 2-minute dark frame; or use my dusty V-band flat on a pristine R-band image. It is nice to be able to retrieve the raw image, and do a corrected reduction!

15.7 Considerations Related to Image Analysis

15.7.1 Are E and ? constant across your entire FOV?

In Eq. 4 and Eq. 5, we determined the plate scale and image orientation by measuring a single ‘calibration pair’, at one location in the image field of view. It is reasonable to ask, ‘Are those values the same across the entire field? The answer is, ‘You won’t know unless you check your system’.

For the systems that most double-star observers use, having relatively long focal-ratio telescopes (F/6 to F/10 or longer) and relatively narrow image fields of view (less than a degree), most likely you won’t see any significant variation in E or ? across the field. Nevertheless, it is conceivable that your system may have some optical aberration that affects E or ? ? field curvature or pincushion distortion, for example. Therefore, it is worthwhile to do a one-time check of your system. Take a series of images of a few ?calibration pairs?, moving the telescope slightly to position the ?calibration pair? near each of the four corners, and near the center of your field of view. Calculate E and ? separately for each image, and for each ?calibration pair?. If there is no significant change in E or ? across the FOV, then you can be confident that your system’s image scale and orientation are indeed ?constant?.

Suppose that your system does have a non-constant E or ?. What then? This isn’t a fatal issue. Depending on your method of image analysis, there are straightforward ways to deal with it. If the values of E or ? are constant over the center half of your FOV, only changing noticeably near the corners, then just be sure to put you target pairs within the ’sweet region? of the FOV, and avoid the corners of the frame.

If you are using ‘astrometric fitting’ to determine the RA, Dec coordinates of the two stars in a pair, consider using higher-order plate constants, which can accommodate the effects of changing E and ? across the field. ?First-order? plate constants implicitly assume unchanging E and ?, whereas quadratic, cubic, or 4th-order plate constants can model most optical aberrations.

15.7.2 WDS 'Calibration pairs' and 'Synthetic calibration pairs'

Using a wide calibration pair minimizes the error in your determination of E and ?. The ?calibration pair? should also be reasonably close in the sky to your targets for the night. This will minimize any errors that might be introduced by field rotation (due, for example, to imperfect polar alignment of your telescope mount).

Where do you find useful 'calibration' pairs? The WDS contains a link to a set of calibration pairs, whose orbits are well-attested, or which are known to be relatively fixed. These are commonly used. Most of these catalogued ?calibration pairs? tend to be quite close (a few arc-seconds or less).

If you think through the math involved in the 'Calibration pair' method, you'll recognize that it is advantageous to have a calibration pair that is reasonably widely-spaced. If the stars are separated by only a few pixels, then an error of a fraction of a pixel in determining their centroids can be a sizable fraction of the total separation; this means that the determination of plate scale (E) may be uncertain by a sizable percentage. Similarly, if the pair is separated by only a few pixels then a small error in the centroid of either star can result in a sizable error in the calculated image orientation (?). In general, you are advised to select ?calibration pairs? whose separation is at least 10 times the FWHM of your image, and whose components are reasonably equal in brightness (say within ± 0.5 magnitude). If your system has high resolution (say, $\Delta\theta < 0.5$ arc-sec), and your site has excellent seeing (FWHM $\sim$ 1-2 arc-sec), then the WDS 'calibration' pairs will probably work nicely for you.

If the WDS 'calibration' pairs are not appropriate for your situation, then you can make your own with your Planetarium program. Widely-used programs such as THESKY and SKYMAPPRO that use the Guide Star Catalog as their primary stellar database are just fine in this regard. Pick any two stars that are nicely placed in your image, and separated by 10-20X FWHM. From your planetarium program, determine their RA, Dec coordinates. Then, use equations Eq. 1 and Eq. 2 to determine their separation and position angle. Now you can use that pair of stars as a 'calibration' pair for your system. (Some planetarium programs - THESKY is one - will calculate the separation and position angle for you, saving you from the calculations of Eq. 1 and Eq. 2.) Even better, you can use several different star-pairs, to confirm that your calibration factors (E and Δ) do not change noticeably with different calibration pairs. If you measure several 'calibration' pairs (WDS or synthetic) to determine E and Δ, use the average determined values for reduction of your target pairs.

15.7.3 Summing Images

In general, only the bare minimum of image processing should be done to your science images. In particular, only 'linear' operations should be done (i.e. no sharpening or deconvolution!)

There are situations where it may be useful to align and add multiple images before measuring ρ, θ. Summing is a linear operation, so it is allowed as a way to improve the SNR (however note the discussion of dynamic range above). Reduce your images (flats, darks, and bias) before summing them.

15.7.4 What if I can't get an astrometric match to my image?

It happens occasionally that a relatively bright double star is located in a sparse field, so that when you take the necessarily short exposure image to avoid saturating the double star, you don?t capture a sufficient number of field stars to make a good astrometric fit. Your software will report 'unable to match' or some similar error message. There are two tricks that can help in this situation.

Most image-processing programs can align and stack (add) multiple images. This will increase the signal from faint field stars, but it is not in itself a cure-all, because if the original 16-bit image was close to saturating on the primary star of your target pair, then summing several images would only aggravate that problem. Some image processing programs (e.g. MPO Canopus and MaximDL) will sum the images in 32-bit arithmetic, and store the summed image as a 32-bit file. That essentially eliminates the ?numerical saturation? problem.

You may be able to get an astrometric fit with a longer-exposure image ? long enough to bring out the faint field stars to enable the program to ?match? the image to its star catalog. Your target pair will, of course, be saturated on that long-exposure image, but you can use the transformation matrix (or image scale and orientation) from the long-exposure image to analyze your 'short exposure' image.

This approach ? using the transformation determined on one image and applying it to a different image ? may seem to be playing fast and loose with the astrometry, even if the two images are taken sequentially and of the same field of view. The reason that it is less risky than it seems is that the separation and position angle of the target pair depend on their positions relative to each other, not on their absolute pixel coordinates. Refer back to Eq. 4 and note that if a constant number were added to both x1 and x2, the calculated separation wouldn?t change. The same is true of the calculated position angle ? the calculated ? and ? are insensitive to small shifts between the images. If the telescope moved a few pixels between the long- and short-exposure images, the relative positions of the primary and secondary are unchanged. If the telescope and camera are well-behaved and if the ?long? and 'short? exposures are taken sequentially with no jostling of the camera or mount, and there is no risk of the camera rotating in the focuser between images, this method works fine.

15.8 Accuracy and Reliability

All scientific measurements should be accompanied by an estimate of their accuracy. This estimate can sometimes be based on theoretical models (such as Eq. 8), but these models contain a host of assumptions that may be difficult to justify. (For example, Eq. 8 implicitly assumes that the noise is truly random and uncorrelated from pixel to pixel ? it takes no account of fixed-pattern noise such as dust donuts). The best that can be done in many cases is to estimate the accuracy of your measurements by examing the data and measurements themselves.

15.9 Assessing the accuracy and Reliability of your measurements

Assessing the quality of your double-star measurements is a bit tricky, because for most pairs, there isn't a 'textbook answer' that you know is correct. You measure ?= 45.6 tonight. A decade ago, someone else measured ?= 46.2. Who is right? Maybe both are ? the pair's relative orientation may very well have changed by a fraction of a degree (or more) in the intervening years. Maybe one is accurate, but the other is mistaken. Maybe both measurements are statistically the same, say, for example, if both measurements are uncertain to 1 degree.

Practices that enable you to assess the accuracy and reliability of your measurements are:

* make multiple measurements of your target, by taking a handful of images on each of two or more nights

* examine the internal consistency of your measurements (both the standard deviation and the full range)

* include a few well-attested pairs in your observing plan

The average of several measurements is more reliable than any single measurement (this applies to almost all measuring activities, not just double stars). By making multiple measurements (from different images) and averaging the results, you improve the reliability and reduce the probable error in the reported value, because you are ?averaging down? the effects of noise and other image artifacts. Making images of the pair on two or three different nights will help prevent accidental errors, such as imaging the wrong star, or being misled by a passing asteroid.

Making (and analyzing) multiple images is also meritorious because the spread of calculated values gives you some insight into the accuracy of your result. For example, if all of your position measurements fall within 0.2 arc-sec of the average value, you can report that your position is accurate to 0.2 arc-sec. This helps other researchers interpret your data, and compare it to other people's measurements. Or, suppose that you take 6 images, and all of the position/centroids are nearly the same (0.2 arc-sec, say), except for one that differs by 1.5 arc-sec. That is a sign that there is something odd. Examine all of the images ? is the ?outlier? unusual or corrupted in some way (cosmic ray hit near the target star? dimmed by a passing cloud? affected by an asteroid passing by?) Or is it perhaps the only ?good? image in the set, and the only accurate measurement? Critical examination may help you decide what to do ? toss out the one discordant image, toss out the 5 corrupted images, or conclude that a fresh batch of images should be taken.

I always try to include one well-attested pair in each night's list of targets. If my subsequent reduction matches the published ?,? for the pair, fine. But if my reduction of this ?well attested? pair is significantly different from its published value, that may indicate that something went awry. The situation needs to be investigated and resolved before I have confidence in the measurement of other pairs from that night.

Including these ?known? pairs in your reports is also a useful discipline. It gives the user of your data an opportunity to assess the quality of your measurements (of this particular pair), and apply that judgment to other pairs in your report. If you don?t include a few ?known? pairs in your report, then the user has no way of assessing the relative quality of your data.

By the way, in this context it is worth noting that when you publish your measurements and they are entered into the WDS, they are permanently tagged with your name. For good or ill, future astronomers will not only be able to see your measurements, but they will also see that you were the observer who made/reported them. So, if you are not confident in the accuracy and reliability of your measurements, it is better to repeat the observation/analysis, rather than to publish dubious results. Your astronomical reputation may depend on it!

Both for the benefit of the astronomers who use your data, and for your own peace of mind, it is a good idea to (at least once) measure a few 'calibration pairs' (available on the WDS). I recommend picking a range of pairs, from quite wide to as close as you can imagine splitting (say ~ 3 pixels). By comparing your results to the ephemeris for each pair, you will confirm that your measurements are accurate and reliable (to within your uncertainty). Perhaps more importantly, you will get an idea of the limits of your system's reliability. If your equipment can?t reliably measure pairs closer than 3 arc-sec, for example, then you know to concentrate on wider pairs.

15.9.1 Precession

Because of the way the celestial coordinate frame is defined, the orientation of the celestial coordinate system is not permanently locked in place - it changes slowly (but predictably) as the Earth's rotational and orbital parameters evolve. Hence, celestial positions may be referred to the 'equinox and pole of 2000' (J2000), or 'equinox and pole of the epoch of observations' (i.e. the coordinate frame as it existed at the time the image was taken). At the level of accuracy that we?re talking about here (fractions of an arc-second), a star's celestial coordinates change noticeably in just a few years.

Of course, the distance between two stars isn't affected by precession. But the position angle is affected by precession, because the direction toward North ? the reference line of position angle ? is continuously changing as the position of the north celestial pole wanders.

Because of the heritage to the days of filar micrometers, the convention is that a pair's position angle is reported relative to the pole and equator of the date of the observation. (If you set up your filar micrometer by monitoring a star's drift with the clock drive off, then you were automatically referring to the instantaneous pole at the time of your observation). But, if you do an astrometric match of your image to a standard astrometric star catalog, your transformation will report the RA, Dec based on the pole position of the epoch of the catalog (normally J2000 for modern catalogs). So, if you make your measurements based on astrometric fitting, you may need to correct them for precession before reporting them.

I say 'may' for two reasons. First, the precession-correction is greatest near the celestial pole, and it shrinks rapidly once you are more than about 10 degrees from the pole. For declinations less than about 80 degrees, you can safely ignore this tiny correction, at least until around 2050 if you are using a modern J2000 star catalog for astrometric fitting of your images.

If you are involved in a project where precession correction is important, refer to Chapter 22 for the relevant equations and instructions. Alternatively, if you use MPO Canopus, its double-star utility has an option to correct the position angle for precession before displaying it.

15.10 Reporting Your Measures

A double star measurement that languishes in your observing notebook is of no value to other astronomers! The Washington Double Star catalog is the IAU's official repository of double-star measures (and other information related to double stars, such as delta-magnitude and color indices). However, you cannot submit measures directly to the WDS. Instead, measures are published in the scientific literature, and the managers of the WDS then enter published measures into the official catalog.

The principle US venue for reporting double-star measures is the quarterly Journal of Double-Star Observations (www.jdso.org), published at the University of South Alabama. Although this is a US publication, the editors welcome contributions (in English) from anywhere in the world. Distribution is free over the internet.

The Webb Society (http://www.webbdeepsky.com) Double Star Section publishes double star measurements in its annual Circulars, making them available to other observers and to the WDS.

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Chapter 16
Lucky Imaging

Rainer Anton

16.1 Introduction

Digital recording of double star images, for example with a modern CCD camera, offers a number of major advantages: Position data can be directly analysed in the computer, and the image is permanent, and can be re-called for future reference. Another benefit of direct imaging is that brightness differences of the components can be measured, which is especially interesting for pairs with contrasting colours.

Usually, the resolution and accuracy is less limited by the telescope, rather than by the seeing, as is the case for all imaging methods, especially, when using long exposure times. However, there are ways to compensate, or at least reduce seeing effects, for example by adaptive optics, or by 'lucky' imaging. This means to 'freeze' the moments of good seeing by using short exposure times, and select only the best frames out of a large number. Details of this technique as applied to imaging of double stars will be described in the following.

16.2 Seeing and resolution

Even under good seeing conditions, the size of the seeing disc is rarely smaller than 1 arcsec, which is larger than the Airy diffraction disc of modest amateur telescopes. The theoretical resolution is usually referred to as Rayleigh or Dawes limits. This is discussed in detail in chapter 11 by R. Argyle ?. As an example, for an aperture of 20 cm (8 inches), the full-width at half-maximum (FWHM) of the central peak is 0.57 arc seconds, at a wavelength of 550 nm. For resolving close double stars, the limits would be 0.69 or 0.58 arc seconds, respectively. These limits are somewhat arbitrary, and can in principle be exceeded, both by visual observers and by imaging techniques.

While these values are of interest for estimating the splitting power of a telescope, angular resolution is not the only criterion for the accuracy of double star measurements. In fact, most important is the accuracy of determining the positions of the centroids of the seeing discs of the components. Provided that both are symmetric or at least similar, this is a matter of resolution of the image itself, i.e. the size of the pixels of the CCD camera in relation to the focal length of the telescope. While relatively long exposure times help in averaging image distortions by seeing effects, the theoretical resolving power can thus hardly be reached.

16.3 Lucky imaging

Generally, the seeing varies with time, both at low and high frequencies. There are almost always some moments of better seeing, even under conditions far from optimum in an average. Thus, the idea of lucky imaging is to freeze the ?good? images with short exposure times, often down to the range of milliseconds or even below, as a compromise determined by the star brightness and seeing frequency. This is essentially the same technique as is widely used by amateurs and professionals on all kinds of celestial objects, including planets and other extended objects. The question is how to identify and select the ‘good’ images. This is not always easy, and will be discussed below. Even the best images are virtually never perfect. Therefore, one has to register and stack a number of these to average out residual image distortions. As a result, the effective size of the seeing disc will be significantly reduced, with particular benefit for splitting and measuring close pairs. Also, the accuracy of measuring wider pairs will be increased because of sharper peaks. In addition, image noise, which is an issue because of the typically short exposure times, will be reduced, which helps for imaging dim companions of pairs with large differences of their brightness.

In some respect, lucky imaging is an alternative (or even supplemental) method to adaptive optics, which, however, is usually not accessible for amateurs. By careful selection and superposition of the ‘lucky’ frames, the resolution can be pushed to near the theoretical limit even under non-optimum seeing conditions. It is demonstrated in the following, with representative examples, that virtually diffraction limited images can almost routinely be obtained with modest amateur telescopes with error margins of position measurements well below 0.05 arc seconds. Besides the seeing, this depends more on the resolution in the image than of the telescope.

16.4 Choice of cameras

As stated above, lucky imaging requires a sufficiently fast camera. In principle, video cameras are well suited for this. In fact, I started some 15 years ago recording double stars with a low cost CCD video module on tape. This camera was designed for surveillance at infrared wavelengths, and was very sensitive. With my 10-inch Newtonian, I could detect stars up to 10th magnitude. Disadvantages were the fixed image frequency of 25 Hz, and the relatively poor image quality as compared with today?s standards. Later, I used the STV CCD camera from SBIG (Santa Barbara Instrument Group), which offers, besides many other interesting features, variable exposure times between 1 millisecond and 10 minutes. It is also very sensitive, with pixel size of 7.4 m square. However, fast recording is only possible via the analogue video output.

Meanwhile, fully digital and affordable CCD cameras appeared on the market, such as the popular webcams, which, with ever increasing storage capacities of computers, allow for almost loss-free transfer of huge amounts of image data at high speed. A very reasonable compromise between sensitivity, resolution, and price is the DMK series from The Imaging Source (TIS). I am using the black and white versions DMK21AF04, and more recently, the DMK31AF03, which are connected via a firewire interface to my notebook. Exposure times can be set by the accompanying software between 0.1 milliseconds and 10 minutes. For lucky imaging, times in the range of up to a few milliseconds are typical. Series of images are stored as AVI files or uncompressed bitmaps at frequencies up to 30/sec. The field of view can be reduced by setting a region of interest, which saves a lot of hard disc space and increases the image transfer rate.

The main difference of the two DMK cameras is the number and size of the pixels, i.e. 640x480 pixels of 5.6 m square for type 21, and 1024x768 pixels of 4.65 m square for type 31. While the sensitivity of the latter is somewhat less than of type 21, the smaller pixel size helps in sampling close pairs with small telescopes. As a general rule, the image feature to be resolved should comprise at least 2 pixels in order to avoid under sampling (This is a practical interpretation of the Nyquist theorem). For an 8-inch telescope, as an example, the image scale should be smaller than 0.29 arcsec/pix, which would require a minimum focal length of about 3.9 m, when using a camera with pixel size 5.6 m. The effective focal length may be adjusted accordingly by inserting a Barlow lens. On the other hand, over sampling should be avoided, too, as this would reduce the sensitivity, because the star light is distributed over more pixels.

In Table 1, values of the image scale are listed for combinations of my DMK cameras with four different telescopes, which I have used so far: my Newtonian at home, a Schmidt-Cassegrain (C11), and two Cassegrain?s, the latter three in Namibia, mostly with a nominal 2x Barlow. These values are not calculated from the focal lengths (FL), as this would not be sufficiently accurate. Rather, more exact calibrations were obtained in an iterative way by measuring systems with well known and predictable separations. This procedure will be described in more detail below.

16.5 The role of filters

Band filters are useful for mainly three reasons: (i) reduction of the atmospheric spectrum, (ii) reduction of chromatic aberrations of lenses, e.g. Barlow, and (iii)

Table 16.1 Calibration factors (resolution) in arc seconds/pixel for combinations of DMK cameras with different telescopes, as determined from reference double stars. The corresponding resolution limits according to Rayleigh's criterion are given in arc seconds for a wavelength of 550 nm.

Telescope	FL (m)	Rayleigh limit	Camera	
			DMK21	DMK31 with 2× Barlow
10-inch Newt.	1.5	0.55	0.388	0.323
11-inch SCT	2.8	0.49	0.220	n/a
50-cm Cass.	4.5	0.28	0.132	n/a
40-cm Cass.	6.3	0.35	0.097	0.0805

for the production of colour composites. Of course, a drawback of filters is the concomitant strong reduction of the overall sensitivity. With my filters, this amounts to almost 2 mags.

(i) At high magnifications, streaking of star images into tiny spectra by atmospheric refraction and seeing effects becomes noticeable. This can be reduced by a band pass filter, preferably red or even infrared, because the effect decreases with increasing wavelength. As an alternative, a Risley prism would offer a higher transmission. While refraction can be efficiently compensated, streaking by seeing effects only to a lesser extent. Another benefit of using a filter is the reduction of anisoplanatic distortions. The latter will be discussed below.

(ii) Lenses are usually not sufficiently corrected in the infrared, where the sensitivity of the CCD chip of the camera is still high. Again, a band filter reduces chromatic aberrations, and results in sharper focus. Therefore, I always insert a filter, when using a Barlow.

(iii) When using a b/w camera, colour images can be composed from images taken with different filters, e.g. R, G, B or IR. Because the sensitivity of the CCD chip varies with wavelength, exposure times have accordingly to be adjusted, in order to obtain a reasonably realistic colour contrast. An example will be illustrated at the end of this chapter.

16.6 Setting the exposure time

For lucky imaging, the exposure time should be as short as possible, or at least adapted to the seeing. One has to choose a compromise between signal-to-noise ratio and frequency of the seeing. As an example, the sensitivity of the DMK21 camera is characterised in figure 19.1. For a number of double stars, the exposure time needed to obtain a reasonable signal-to-noise ratio of the dimmer component is plotted versus its brightness. All data refer to the configuration with 2x Barlow lens and red filter attached to a 10-inch-Newtonian telescope at effective f/12. The scatter, besides some ambiguity regarding the term ?reasonable?, is caused by several effects: colour of the star, sky transparency, and seeing. Nevertheless, the approximated straight line indicates a linear increase of the minimum exposure time with decreasing intensity, as expected, because the magnitude varies with the logarithm of the intensity. Without Barlow and filter, the sensitivity is greater by one to two mags.

When dealing with large differences of the brightness of the components, the brighter one will be overexposed. This may affect the accuracy of position measurements. Examples will be illustrated below.

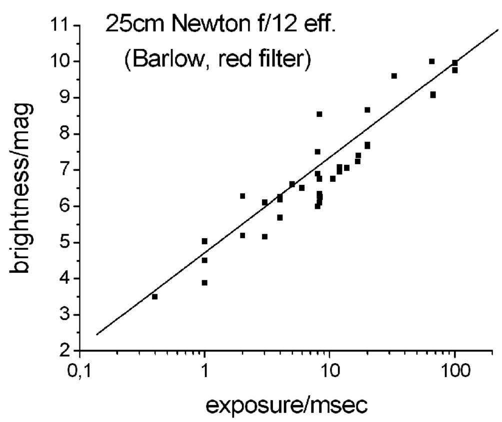

Fig. 16.1 Minimum exposure time required for recording a star versus its magnitude. Data are obtained with a DMK21 camera at my 10-inch Newtonian. Note logarithmic scaling. The slope of the approximated straight line corresponds to an increase of the effective sensitivity by about 2.5 mags for a tenfold increase of exposure time.

16.7 Selection of images

Recording of a few thousand images is done within a couple of minutes. Processing takes much more time, mainly because in most cases, selection of good images is not easily done with automatic programs. The reason is that the 'lucky' image is almost never perfect, even under good seeing conditions. Therefore, considerable care has to be taken to judge the image quality. This is illustrated in figure 19.2 by representative images of the double star theta Gruis (JC 20 AB, WDS 23069-4331), recorded in 2008 with a DMK21 camera and a 50-cm-Cassegrain with Barlow and red filter (see table 1). The visual magnitudes of the components are 4.5 and 6.6, and the separation is 1.5 arcsec. Seeing conditions were average. Exposure was set to 8.3 msec as compromise between speed and signal-to-noise ratio of the faint companion, while the main star was occasionally slightly overexposed. Out of a total of 1880 original frames, 88 with reasonable quality were selected for further processing by visual inspection. Six of the best are shown here, which demonstrate the residual fluctuations of the image quality. None is really perfect, although no. 1839 is very close. Criteria for selection were the roundness of the image of the main star, the shape of the diffraction ring, and the appearance of the dim companion. These criteria can hardly be simultaneously accounted for by automatic programs. In particular, an algorithm relying on the brightest pixel(s) would not sufficiently characterise the overall image quality. Likewise, an algorithm based on the centre of gravity would fail, because the diffracting ring is in most cases not complete and rather asymmetric. Therefore, I prefer to select the best images by visual inspection, although this is rather time consuming. A good help is the public-domain program ?VirtualDub?. Sorting of images is just done with mouse clicks.

The images in figure 19.2 are enlarged, so as to show the original pixel structure. It is clear that the peak centroids can in principle be determined with sub-pixel accuracy, as will be demonstrated in figure 19.3 below.

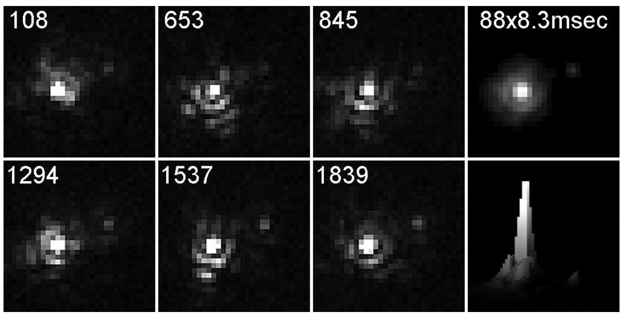

Fig. 16.2 The double star theta Gruis, imaged with a 50-cm Cassegrain at f/18. Six of the best original frames are marked with their numbers. The central sections of 64 x 64 pixels are shown, and enlarged to show the original resolution. Note the fluctuations of the diffraction rings around the main component. In the superposition of 88 frames with equivalent quality (top row, right), a more or less continuous ring is formed. Also, the image of the faint companion is better confined. The image at lower right is a 3-d view of the intensity profile of the upper image. North is down, east is right, as in all other images.

16.8 Image Processing

Once selected, registration and stacking of the images can usually be done automatically, with public-domain programs like REGISTAX or GIOTTO, for example. For the system theta Gruis shown in fig. 19.2, the result of superposing the 88 best frames is shown at top right. The star image appears rather symmetric, the diffraction ring is almost fully developed, and the dim companion is clearly visible. However, at this stage, the definition of the peak centres is only accurate to one pixel, while it is obvious that the peak centre does not necessarily coincide with the centre of one pixel. A significant improvement is possible by re-sampling. This is preferably done with the original frames, because this allows registration with sub-pixel accuracy with respect to the original pixel size, as is illustrated in fig. 19.3. The same single frames as shown in fig. 19.2 have been re-sampled by multiplying the number of pixels in x- and y-direction by a factor 4, with concomitant interpolation of the pixel values with a bi-cubic function. This results in smoothening of the intensity profiles, especially after stacking, such that the peak centres can be determined with correspondingly increased accuracy. Also, re-sampling makes selection of good frames by visual inspection much easier. It should be noted that in this case the large difference in brightness of the components resulted in occasional overexposure of the main star, as can be seen in some of the single frames. Therefore, the intensity profile in the superposition is somewhat truncated, and the peak width appears greater than expected. Nevertheless, the peak centre is well defined, especially in the image resulting from the process with interpolation.

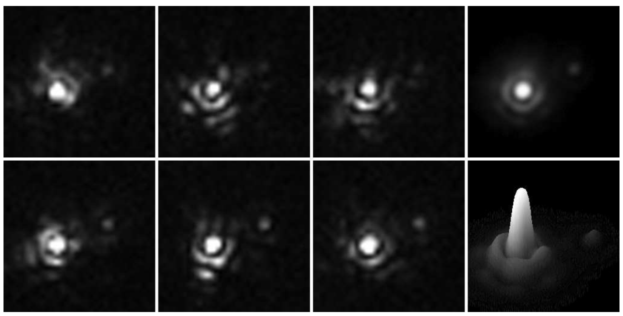

Fig. 16.3 Same as in fig. 19.2, but the original frames had been re-sampled with a factor of four, while the pixel values had been interpolated with a bi-cubic function. The image at top right is a superposition of 88 re-sampled frames. As a result, the intensity profiles are smoothed, and the centres of the peaks can be determined with sub-pixel accuracy, referred to the original pixel size.

After calibration of the image scale and orientation (this will be discussed below), the measurement resulted in 112.5 degrees for the position angle, and 1.50 arcsec for the separation, which correspond to extrapolated literature data within 1 degree, and 0.02 arcsec, respectively.

16.9 Anisoplanatic effects

When selecting frames, one has to be aware of anisoplanatic distortions, which are caused by the limited size of the ?seeing cells? in the atmosphere. The typical isoplanatic field size is of the order of 5 arc seconds in the visible, and increases for longer wavelengths. It can be much greater under very good seeing conditions. The dependence on wavelength is one reason why the yield of lucky images is usually greater when using a red or even infrared filter. Anisoplanatic effects are not always obvious at the first glance. In fact, it occurs that good looking images are distorted, such that the relative positions of the stars are shifted. This is best seen when playing back the series of selected images. Wide pairs are more likely to be affected than close ones. For a system with separation of about 30 arcsec, I have observed displacements of up to ± 0.5 arc seconds even under seeing conditions, which were generally not so bad. Such frames are discarded, when noticed. In contrast, I once experienced moments of nearly no distortions during recording the wide (double) pair eps1-eps2 Lyrae, with separation of about 208 arcsec. Figure 19.4 illustrates the result of anisoplanatic distortions for the system DUN 230 in Sagittarius (WDS 20178-4011), with components of 7.4 and 7.7 mag, separated by about 10 arcsec. It was recorded with a 50-cm Cassegrain at f/9 with red filter. The exposure time was 20msec, and 107 selected frames were aligned with respect to the main component A, and superposed. As a result, thanks to lucky imaging, the peak width of A of 0.29 arcsec (FWHM) is close to the theoretical value for a wavelength of 650 nm (red). In contrast, that of component B is larger by more than a factor of 2. Moreover, component B appears to be dimmer than expected from the magnitudes listed in the WDS. The reason is that there are still frames which are affected by anisoplanatic distortions, despite careful selection. It should be noted that no non-linear stretching of the histograms has been applied.

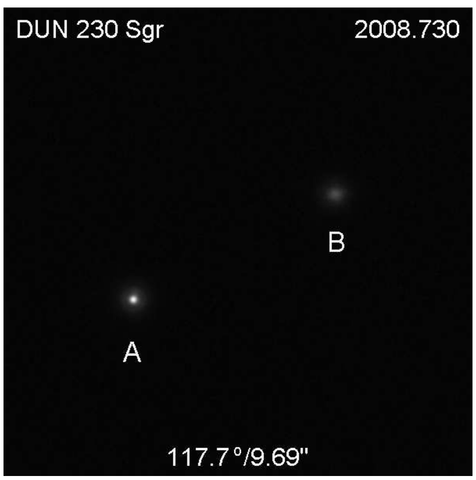

Fig. 16.4 Left: The pair DUN 230 in Sagittarius, imaged at the date indicated at top right. 50-cm Cassegrain, 107 frames x 20 msec. The measured position angle and separation are given at the bottom. Right: Plot of the normalised peak profiles of components A and B. Frames were aligned with respect to A. Note the difference of the peak widths, which is caused by anisoplanatic distortions.

Measurements:

16.10 Calibration of the image scale

Calibrating the image scale can be done with various methods, which are for example discussed in chapter 14 in this book (Tom Teague?). I am doing this in an iterative way by measuring a number of double stars, which are well documented in the literature either as so-called ?relfix?, or with trustworthy predictable movements. This may even include some fast moving binaries. Sources for literature data are mainly the Washington Double Star Catalogue (WDS), the 4th Catalogue of Interferometric Measurements of Binary Stars (in short: ‘speckle catalog’), and the 6th Catalogue of Orbits of Binary Stars. All are available online, and are frequently updated.

Starting with a calibration constant calculated from the telescope and camera data, the image scale is fine-tuned such that the average deviation and the standard deviation assume minimum values. This is illustrated for calibrating my 10-inch Newtonian with Barlow and DMK21 camera in fig. 19.5. A total of 169 double stars have been measured, of which 58 were used for calibration. For all systems, the residuals of the separations (delta rho) are plotted in fig. 19.5. Statistical analysis of the data from the calibration systems (open circles) resulted in a minimum standard deviation of ± 0.03 arcsec, with range between maximum and minimum of ± 0.1 arcsec, after adjusting the scale constant to 0.388 arcsec/pix, with error limits of $\pm$ 0.001 arcsec/pix, or $\pm$ 0.5%. This value is listed in table 1 above. The absolute total error limits are given by the sum of both contributions. These appear as curves in fig. 19.5. Clearly, at small separations, the statistical error determines the accuracy, while for large distances, the dominant contribution is the error of the calibration constant. It should be noted that this also applies to the data taken from the literature, although the error margins are usually not reported. This partly explains the strong increase of the scatter for wide systems. It should also be noted that the accuracy of position measurements does not depend on the separation itself, except for very close systems with overlapping intensity profiles.

16.11 Determining the position angle

While the position angle is referred to the north direction, and counted via east, south and west, it is much easier to determine the east-west direction. This is simply done by recording a series of images with the telescope drive temporarily switched off. Superposition of the images in the computer results in a more or less well defined line (‘trail’), depending on the seeing, from east to west. The angle with respect to the pixel rows can be measured with an average error of about $\pm$ 0.1 degree. It is good practice to record such trail just before or after recording the double star in question, in order to make sure that the geometry has not changed intermediately, for example by unintentional rotation of the camera. This is in particular important, when the telescope mount is not exactly adjusted to the polar axis, and for

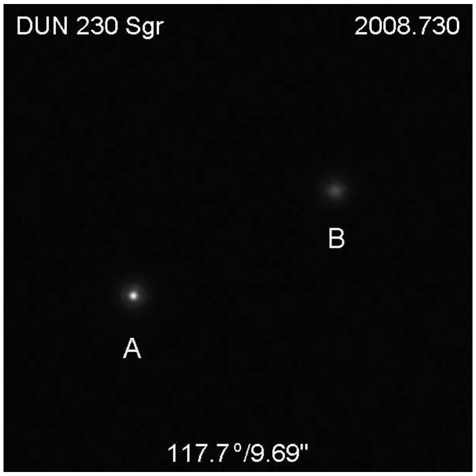

Fig. 16.5 Plot of the residuals delta rho of the separation rho versus rho. Semi-logarithmic scale. Open circles represent systems, which have been used for calibration of the image scale, full circles denote all others. The curves mark the total error limits.

alt-azimuth mountings. Then, trail recordings have to be made frequently, in order to interpolate with respect to field rotation.

The position angle of the double star is calculated from simple geometry. The accuracy depends on the separation, because of the fixed resolution, which is determined by the pixel size. Thus, variation of the position by say one pixel perpendicular to the system axis has a much stronger effect on the angle for short distances than for wider ones. This is shown in fig. 19.6. The residuals of the position angle are plotted versus the separation, for those systems, which have been used for calibration of the image scale (see fig. 19.5). For wider systems, the error margin is typically below $\pm$ 1 degree, but it increases up to 3 to 4 degrees for systems with separations close to the resolution limit of the 10-inch telescope.

16.12 Accuracy of measurements

In the example described above, statistical analysis of systems used for calibration resulted in a standard deviation of the residuals of separation measurements of $\pm$ 0.03 arcsec, for the DMK21 camera at a 10-inch Newtonian at f/12. A similar value is expected for the separations themselves. This is illustrated in fig. 19.7 for the case of the binary STF 3050 in Andromeda by comparing measurements from lucky imaging with data from the speckle catalogue, which are generally deemed as fairly accurate, depending on the size of the telescope. The components exhibit almost equal brightness (6.5 and 6.7 mag), and the period is about 320 years. The system was analysed four times in recent years with lucky imaging with the equipment

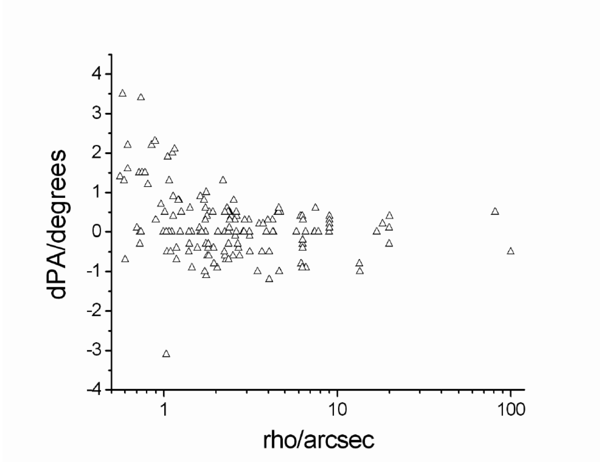

Fig. 16.6 Plot of the residuals of the position angle versus rho. Only systems used for calibration as in fig. 19.5 are included here. The increase of scatter towards small separations is mainly caused by the fixed image resolution.

named above. In fall 2010, the separation has increased to about 2.3 arcsec, and the position angle to 337 degrees. Both are further increasing. Fig. 19.7 a) shows a representative image of 2009. In figs. 19.7 b) and c), own measurements are plotted together with speckle data, and with the currently assumed ephemeris.

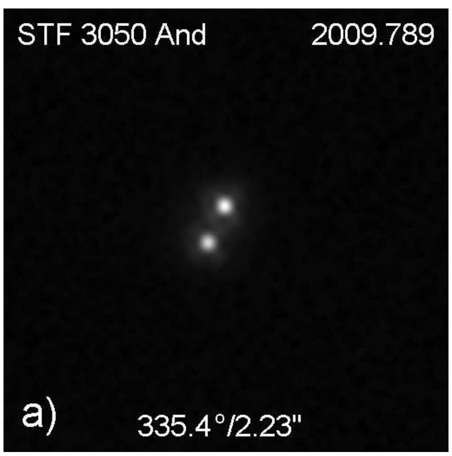

Fig. 16.7 The binary STF 3050 in Andromeda (135 frames x 12 msec), recorded at the date given at top right. Measurements of position angle and separation are indicated at the bottom.

The data from lucky imaging follow the trend of speckle data. It is remarkable that the scatter is comparable, although most of the speckle measurements have

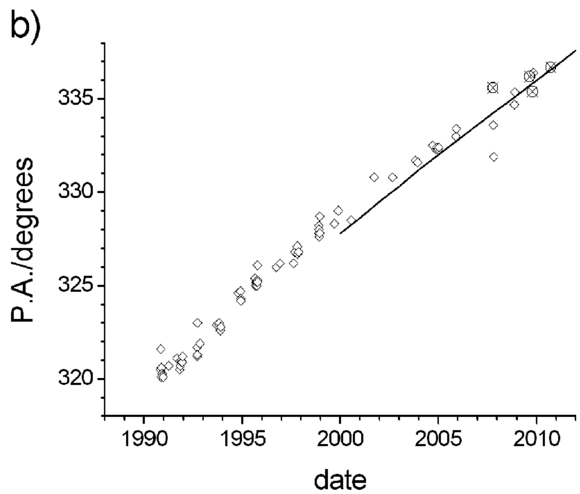

Fig. 16.8 b) + c): Position angle P.A. (b), and separation rho (c) of the binary STF 3050 versus date. Open rhombs mark speckle data, encircled crosses are own measurements. Curves represent the ephemeris from 2000 to 2012.

been done with larger telescopes. Interestingly, the separation increases faster than expected from the ephemeris. The latter is based on orbital elements calculated in 1977, with quite high error margins, because only less than half of the orbit is documented by measurements. The difference has now grown to greater than +0.15?, which is much larger than the error margin of both speckle interferometry and lucky imaging. Obviously, the orbit awaits re-calculation some days. There are many other more or less similar cases, to which special attention should be paid by accurate measurements.

Another example, which demonstrates the accuracy of measurements near the resolution limit, is the close binary zeta Bootis (WDS 14411+1344), which is shown in fig. 19.8 a). Although the intensity profiles of the components with brightness 4.5 and 4.6 mag partly overlap, the peak centres are clearly separated. Because of strong overlapping of the intensity profiles of the components, the peak positions have been corrected by decomposition techniques. Results of measurements from 2008 through 2010 are listed in table 2, together with residuals. During the last years, the separation has decreased to about 0.5 arcsec, which is smaller than Rayleigh?s limit of resolution of the 10-inch telescope, when using a red filter. While the average deviation of the separation from the ephemeris of +0.03 arcsec is well within the error limits, the position angle seems to systematically be greater than expected. The reason is not quite clear yet. Deviations from extrapolated speckle data seem to be somewhat less. In fig. 19.8 b), separations from speckle and from lucky imaging are plotted versus time. Again, the scatter is comparable, despite the small separation.

Table 16.2 Measurements of the position angle (PA) and separation (rho) of the pair zeta Bootis. Residuals are referred to the corresponding ephemeris. See also fig. 19.8.

date	PA	residuals (degrees)	rho	residuals (arcsec)
2008.317	298.2	+2.9	0.62	+0.05
2008.344	297.4	+2.1	0.56	-0.01
2009.252	298.5	+4.0	0.58	+0.03
2009.260	296.6	+2.1	0.62	+0.07
2009.301	296.3	+1.8	0.59	+0.04
2010.419	295.8	+2.2	0.53	+0.01
2010.42	297.9	+4.3	0.52	0
	average	: +2.8	average:	+0.03

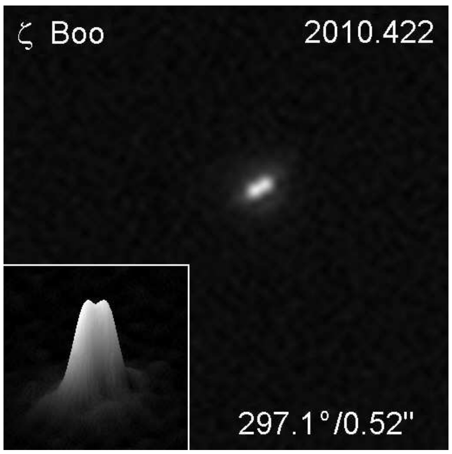

Fig. 16.9 Left: The binary zeta Boo, imaged with a 10-inch Newtonian at f/12 at the date indicated at top right. DMK31 camera, 103 frames x 3.3 msec. The inset shows a 3-d view of the intensity profile. No non-linear stretching of the histogram has been applied. Position angle and separation as measured from this image are indicated at the bottom. Right: Plot of the separation versus date. Open rhombs are speckle data, taken from the USNO catalogue, crosses are from lucky imaging. Solid curves represent two different calculations of the ephemeris (USNO).

16.13 Reproducibility

Another aspect of accuracy is the reproducibility. This is checked by repeated measurements of a system within short time, such that the position does not noticeably changes. As examples, the two binary systems zeta Aquarii (STF 2909, WDS 22288-0001) and beta Phoenicis (SLR1 AB, WDS 01061-4643) with periods of 487 and 195 years, respectively, have been observed at several nights within one week in fall 2008 with a 50-cm- and a 40-cm-Cassegrain. Representative images are shown in figs. 19.9 and 19.10, and the measurements of position angles and separations are listed in tables 3 and 4. It is remarkable that in both cases, the scatter of the separation data falls within the range of the standard deviations, although some measurements were obtained with different telescopes. This means that a possible error of the scale factors does not play a role. In fact, the mean value of the separation of zeta Aqr of 2.09 arcsec agrees within 0.02 arcsec with speckle measurements done at about the same epoch. Likewise, the mean of the position angles falls into the range of speckle data. This system is also interesting for another reason. The B component itself is a binary with a companion with period of 25 years. This is not seen in the visible, but has indirectly been detected by speckle techniques in the infrared. It causes periodic deviations of the position of B from the calculated orbit. The recent periastron passage of C with respect to B in 2007 was more clearly seen in the position data than in earlier times, because of more precision measurements.

Table 16.3 Measurements of position angles (PA), separations (rho) of the system zeta Aquarii, obtained with two telescopes and at different nights in 2008. Total mean values, ranges, and standard deviations are given in the last three lines.

Telescope	Date	P.A.($^\circ$)	ρ''
40cm Cass. f/16	2008.732	171.3	2.085
f/32	2008.735	170.9	2.076
	2008.738	170.2	2.113
50cm Cass. f/18	2008.727	170.5	2.089?
	2008.728	170.1	2.108?
	2008.749	169.8	2.090
	mean:	170.5	2.094
	range:	1.5	0.037
	std.dev.:	$\pm$ 0.55	$\pm$0.014

For beta Phe (see table 4), six measurements in fall 2008 resulted in a mean value of separation of 0.39 arcsec, which agrees within the error limit of about 0.02 arcsec with speckle data from about the same epoch, which were obtained with a 4-m telescope [2]. This again demonstrates that the absolute error margin does not depend on separation (when not too small). The error margin of the position angle, however, is increased to about 3 degrees, which is caused by the small separation. This system had been neglected in the years from 2000 to 2008, and the recent position data from both speckle and lucky imaging significantly deviate from the hitherto assumed ephemeris. Based on these data, a new orbit has been calculated, which resulted in a reduction of the period from 195 to168 years. The pair has again been recorded in 2009 with the same equipment, and the position data agree well with the new ephemeris.

As a conclusion, both the accuracy and reproducibility can be deemed as comparable with speckle interferometry, even with telescopes not quite as large as are typically used for the latter method. However, there are limitations, which will be discussed below.

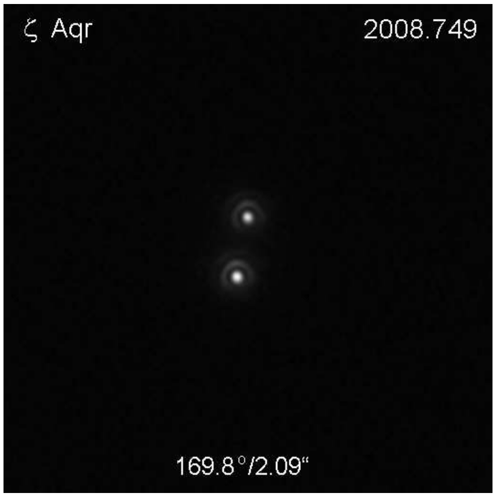

Fig. 16.10 The binary zeta Aquarii, imaged in 2008 with a 50-cm Cassegrain at f/18 (48 frames x 2 msec). Position data obtained from this image are indicated at the bottom.

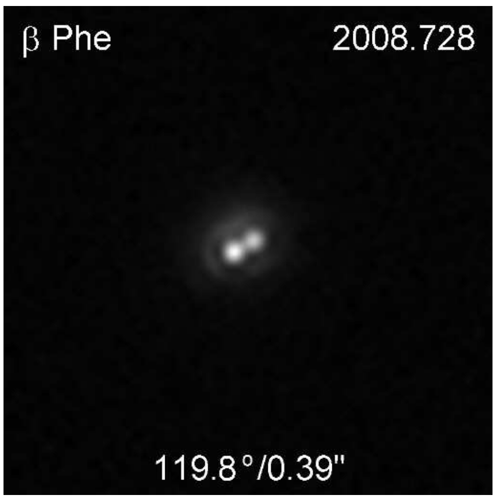

Fig. 16.11 The binary beta Phoenicis, imaged in 2008 with a 50-cm Cassegrain at f/18 (60 frames x 0.5 msec). Position data obtained from this image are indicated at the bottom.

16.14 Dealing with large dΔm pairs

When compared with visual observation, imaging with a camera has a significantly smaller dynamic range. As was already mentioned above in the section on image processing, large differences of the brightness of the components may lead to over-exposure of the main star, which may cause artefacts in the image. In particular, an

Table 16.4 Measurements of position angles (PA) and separations (rho) of the system beta Phoenicis. Total mean values, ranges, and standard deviations are given in the last three lines.

Telescope	Date	P.A.(°)	ρ''
40cm Cass. f/16	2008.740	117.4	0.398 ?
f/32	2008.741	119.2	0.387
50cm Cass. f/9	2008.724	119.4	0.385?
	2008.728	119.8	0.392?
	2008.743	120.7	0.381?
	2008.746	119.7	0.399
	mean:	119.4	0.390
	range:	3.3	0.018
	std.dev.:	± 1.09	±0.007

asymmetric intensity profile may result from a not perfectly collimated telescope or from coma, such that overexposure including the diffraction ring shifts the apparent peak centre of the main star, but not that of the companion. Overexposure can be avoided by insertion of a special filter into part of the field of view, such that the intensity of the bright star is damped, but not of the companion. In some cases, a filter may help, when the components exhibit distinctly different colours. As an alternative, which is applicable in Newtonian or Cassegrain telescopes, the peak centre can be marked by the diffraction cross produced by the mounting of the secondary mirror (‘spider’). This has been used for measuring the binary Sirius (alpha CMa, WDS 06451-1643), with brightness of the components of -1.5 and 8.5. An image is shown in fig. 19.11. While in 2008 the white dwarf companion was lying clear off the diffraction spike, it coincided with it in 2009, when it was again recorded with the same equipment, and the position angle has decreased by about 5 degrees.

16.15 Limitations

From the example of Sirius, one can estimate that a pair with dΔm = 10 mag can no longer be split with this equipment, when the separation gets smaller than about 5 arcsec. Another difficulty arises for pairs with even lower dΔm, when the dim companion is lying on or close to the diffraction ring of the main star. This makes selection of lucky images ambiguous, because of the fluctuations of the intensity in the diffraction ring, as was demonstrated in figs. 19.2 and 19.3. Sometimes, it is a good strategy to stack a large number of unselected frames after aligning for the main star, which may show the dim companion as more or less diffuse speck. This helps in searching for the ?better? frames for further processing. A less critical example is the binary 35 Comae AB (STF 1687 AB, WDS 12533+2114), which is shown in fig 19.12. It was recorded in 2009 with a 10-inch Newtonian at f/12 with Barlow and red filter. The two components with brightness 5.1 and 7.1 mag are cur-

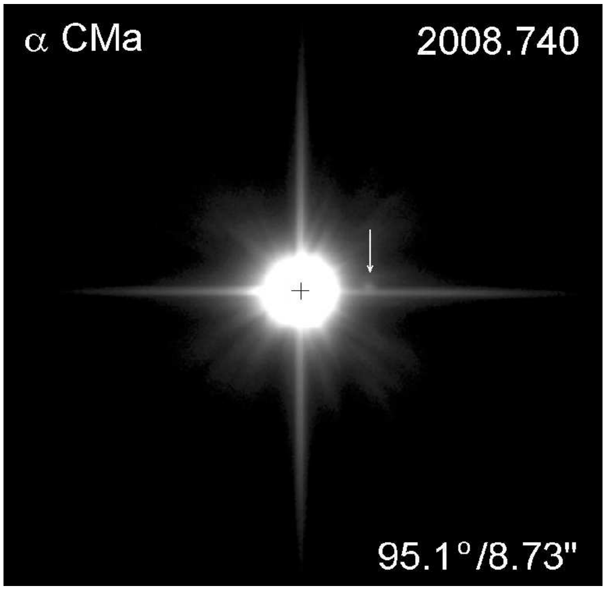

Fig. 16.12 Sirius, imaged in 2008 with a 40-cm Cassegrain at f16 (66 frames x 12 msec, no filter). The diffraction spikes were used to determine the peak centre of the primary. The measured position of the companion (arrow) is indicated at bottom right.

rently separated by about 1.1 arcsec. Thus, it almost coincides with the diffraction ring of the main star, with radius of about 1.0 arcsec for red light. Therefore, the intensity profile of the companion appears to be somewhat distorted, and smeared out along the diffraction ring. The error margins of both the position angle and separation are correspondingly increased.

16.16 Measuring intensities and dΔm

Digital imaging offers the possibility to measure the star brightness in the computer. This can in principle even be done in absolute terms, if the intensity scale can be calibrated. This is not trivial, despite the often cited linear response of CCD devices, because this is rather limited for the type of fast cameras used here, as will be shown below. Furthermore, at least one reference star is required. For double stars, the main component can act as reference, so as to determine the difference of the magnitudes of the components. Intensities are measured by integrating over all pixels comprising the peak, and subtraction of a corresponding background. This has been done on images of the bright star Vega (alpha Lyrae, 0 mag), obtained with the DMK21 and DMK31 cameras at a 25-cm Newtonian at f/12. In fig. 19.13, the signal-to-background ratio is plotted versus exposure time.

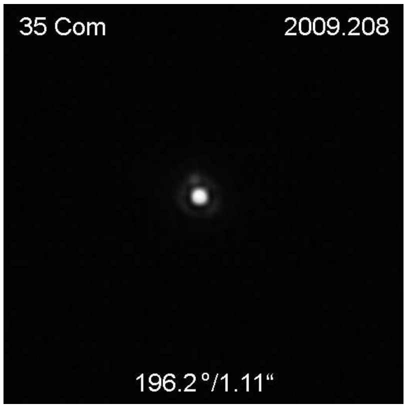

Fig. 16.13 The binary 35 Comae AB, imaged with a 10-inch Newton at f12 in 2009 (100 frames x 12 msec). The contrast of the dim companion, with brightness only 2 mag less than of the main star, is rather low, due to the coincidence with the diffraction ring.

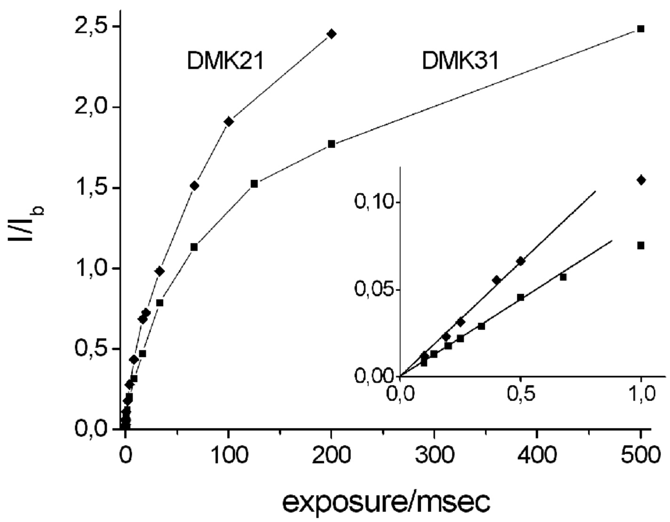

Fig. 16.14 Plot of the ratio of the peak intensity I to the background Ib versus exposure time in msec, measured for the star Vega (alpha Lyr) with a 25-cm Newton at f12 with red filter, and with two cameras as indicated. The inset shows the magnified range of short exposure times up to 1 msec.

Each data point results from a stack of about 200 registered frames, which were not specifically selected. Exposure times were varied from 0.1 to 500 msec. All recordings were made within half an hour at the same night with fairly steady seeing and no clouds. For this bright star, the range of linearity ends at about 0.8 msec, corresponding to a signal-to-background ratio of about 1.0, when using the DMK21 camera. Longer exposure leads to saturation of first the central pixels in the peak, and further of neighbouring pixels. Thus, the area of overexposed pixels spreads radially, which results in a truncated peak profile. In the linear range, the dynamic range in magnitude is estimated as follows: In the processed images, the intensity of the background was found to vary by about one percent. When assuming a minimum detectable intensity of a star image corresponding to a signal-to-noise ratio of one, the range in magnitude would be 5 mag, according to the relation Δmag = -2.5 log(I1/I2).

Measurements of brightness differences in double star systems should be done within the linear range of the camera response. In any case, the accuracy strongly depends on the seeing. With short exposure times, even under seeing conditions better than average, drastic variations of the intensities of the components are common, and these may not even be correlated. This is illustrated in fig. 19.14 for a recording of the binary zeta Aqr in 2009 done with a 40-cm Cassegrain in Namibia (see also table 5 below). This system is well suited for such analysis, as the components exhibit almost equal brightness: 4.34 mag and 4.49 mag in the visual. Exposure time was 8.3 msec. Only the best 53 frames were selected out of a series of 1500, not only regarding the peak shapes, but also the intensities. In particular, frames were discarded, in which the intensities of the components appeared to be too different, or even reversed, or one component was overexposed.

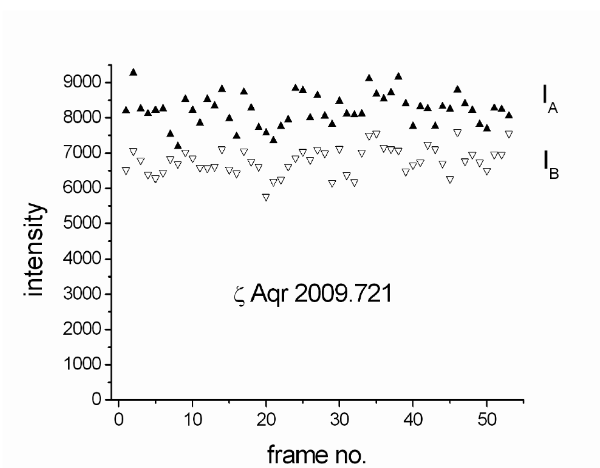

Fig. 16.15 Left: Variations of intensities IA and IB of components A and B of the system zeta Aqr, recorded in 2009, versus the frame number. Only the best 53 frames out of a longer series were selected. Right: Corresponding, calculated differences ? mag. The horizontal line marks the statistical average value of -0.21 mag. Its standard deviation is ± 0.06 mag.

Results of systematic intensity measurements of zeta Aqr, done in 2008 with the same 40-cm telescope and also with a 50-cm Cassegrain, always under seeing conditions better than average, are listed in table 5. In all cases, the same combination of DMK21 camera with Barlow lens and red filter was used, and from each recording, only the best frames were selected for stacking. The resulting average value of the difference of the magnitudes of -0.19 mag is slightly greater than the catalogue value of -0.15 mag. The reason for this difference is not quite clear, but is probably due to the red filter used here. In any case, the difference seems to be real, regarding the standard deviation of less than ±0.02 mag. It should be noticed that these results had been obtained with relatively small numbers of frames. Certainly, larger numbers would be necessary under less favourable seeing conditions.

Table 16.5 Measurements of intensity ratios (second column from right) and differences of magnitudes (right column) of the pair zeta Aquarii during one week in 2008, as well as in 2009. In the left column, the telescope used for the recordings is denoted. In the second column from left, the numbers of stacked frames and exposure times are listed. See also the representative image in fig. 19.9. Mean values and standard deviations are also given.

Telescope	frames × expos.	Date	I_A/I_B	Δmag
40-cm Cassegrain f/32	16 × 12 msec	2008.735	1.196	-0.194
	38 × 8.3	2008.738	1.192	-0.191
50-cm Cassegrain f/9	44 × 2	2008.726	1.192	-0.191
	32 × 1	2008.727	1.203	-0.201
	48 × 2	2008.749	1.171	-0.171
40-cm Cassegrain f/32	53 × 8.3	2009.721	1.215	-0.210
		mean:	1.195	-0.193
		sd:	±0.015	±0.013

16.17 Colour composites

Many double stars exhibit more or less pronounced colour contrast. Famous examples are beta Cygni (Albireo), gamma Andromedae, epsilon Bootis, gamma Delphini, iota Cancri, alpha Canum Venaticorum (Cor Caroli), alpha Herculis (Rasalgheti), or gamma Crucis, only to name a few brighter systems. Interestingly, visual sensation of colour is often different as expected from the spectra. This may be caused by various factors, including different brightness of the components, separation, size of the telescope, or personal perception. All this has often led to remarkable variations of colour designations in the literature. For example, colours of the pair alpha Herculis, with spectra M5 and G5, are seen by different observers as red/greenish, or orange-red/bluish-turquoise, or orange/blue-green. Sometimes, colour perception is even reversed. For example, descriptions of alpha Canum Venaticorum range from white/bluish to yellow/reddish.

Imaging with a colour camera can sometimes yield impressive results, or even help to clarify discrepancies or illusions, as described above, but there are limitations, too. One major difficulty arises from the strong dependence of sensitivity on wavelength. This means that the colour balance has to be calibrated. This can be done with test recordings of reference objects. The author uses b/w-cameras with filters, in order to produce RGB-composites, because of their greater resolution and sensitivity, when compared with colour cameras of similar price range. Reasonable colours are obtained with about equal exposure times in the red and green, which is about doubled in the blue, as a rough estimate, depending on the particular filters. The second difficulty is the limited dynamic range, combined with the variation of sensitivity with wavelength. In particular, in systems with a bright main star of late spectral class, say G to K, and a dim blue companion, which is a rather frequent combination, the former may be overexposed in order to obtain a decent contrast for the companion. This will shift the colour of the main star to white in the composite. It is easier to image a bright, blue star with a dim red companion than vice-versa. Problems are reduced when dealing with pairs with small dΔmag in the visual, i.e. about green. Such an example is the system STF644AB in Auriga. Although the visual brightness of the components is about equal, with 6.96 mag and 6.78 mag, the pair exhibits a striking blue-yellow colour contrast, due to spectra B2 and K3, respectively. This is shown in fig. 19.15. The pair had been imaged with filters in the near infrared, red, green and blue, and the dΔmag values had been determined as described in the foregoing section.

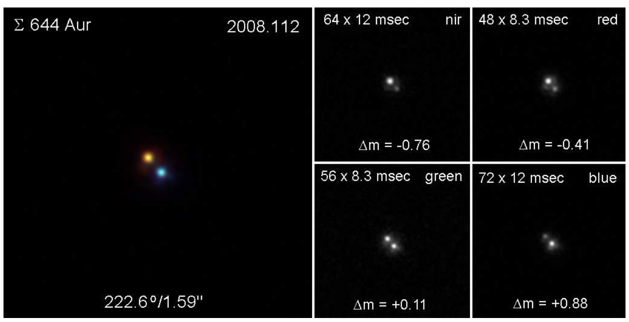

Fig. 16.16 STF 644 Aurigae, left: RGB composite, right: filtered images as indicated. Note smaller scale. Numbers and exposure times of the respective frames are also given. The blue star is designated as main component of the system, although it appears slightly dimmer in the visual than the yellow one. In the WDS, the difference in magnitude dΔm is given as +0.18, which roughly corresponds to the value measured here in green light.

16.18 Concluding remarks

It has been demonstrated with selected examples that lucky imaging allows the user of medium sized telescope to obtain rather accurate measurements of double stars. The key is careful selection and stacking of only the best frames out of longer series, by which seeing effects can strongly be reduced. This improves the precision of position measurements to values better than at least one order of magnitude, when compared with the theoretical resolution limit. It has been shown that even with modest amateur telescopes, the scatter of separation measurements compares well with that of interferometric measurements, which are mostly done with larger telescopes. In principle, the accuracy of measurements from lucky imaging and speckle interferometry should be the same, when performed with the same telescope and camera, because both are based on images. Only the method of analysis differs, namely averaging over a number of images, or averaging over a number of speckles, respectively. Clearly, most important for the resolution and accuracy is the size of the telescope. While lucky imaging appears to be the method of choice for use with modest telescopes, speckle imaging develops its full capacity only with larger instrumentation.

16.19 Acknowledgements

This work has made extensive use of the double star catalogues made available online by the United States Naval Observatory. Special thanks are due to Brian Mason for providing additional data.

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Chapter 17
The DSLR Camera

Ernő Berkó

Introduction

Cameras have developed significantly in the past decade; in particular, digital Single-Lens Reflex Cameras (DSLR) have appeared. As a consequence we can buy cameras of higher and higher pixel number, and mass production has resulted in the great reduction of prices. CMOS sensors used for imaging are increasingly sensitive, and the electronics in the cameras allows images to be taken with much less noise. The software background is developing in a similar way - intelligent programs are created for after-processing and other supplementary works. Nowadays we can find a digital camera in almost every household, most of these cameras are DSLR ones. These can be used very well for astronomical imaging, which is nicely demonstrated by the amount and quality of the spectacular astrophotos appearing in different publications. These examples also show how much post-processing software contributes to the rise in the standard of the pictures. To sum up, the DSLR camera serves as a cheap alternative for the CCD camera, with somewhat weaker technical characteristics. In the following, I will introduce how we can measure the main parameters (position angle and separation) of double stars, based on the methods, software and equipment I use. Others can easily apply these for their own circumstances.

Camera, telescope, technical equipment

What camera can be used for the purpose? Any kind of DSLR camera with interchangeable lenses. It is practical to have a sensor larger that 8 Mpixels, and noise reduction function and computer interface come as an advantage. B (bulb) setting is also required when we take a long exposure time photo. I use a Canon EOS 350D(1), which is no longer on sale. This has an 8 Mpixel CMOS sensor. Each frame covers 3456×2304 pixels, whilst each pixel is 6.5×6.5 microns in size. I set the camera to ISO1600. Today's medium quality cameras comply well with the requirements.

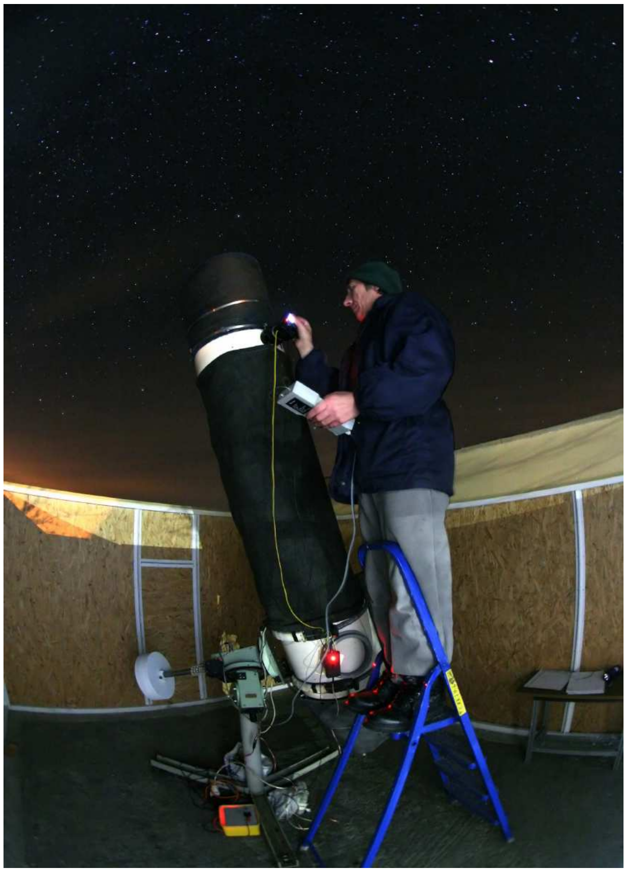

Fig. 17.1 The author in his observatory

What telescope and mount are suitable for the task? Substantive work can be done with any telescope having good optical quality and aperture of at least 20cm (8-inch) or larger. The mount should have a clock drive for the longer exposure times. It should possibly be of stable, vibration-proof built, best with a hand controller, so that it can be set on both axes to any coordinates with the help of slewing motors. It is also useful to have a computer interface, so that it can be controlled from a PC. I use a 35.5cm (14-inch) diameter Newtonion reflector, which has focal length of 2100 mm. This is on a Gemini G-40 mount(2), which has a Kordintor 2000 hand controller unit and RS-232 computer interface.

In order to make the camera-telescope unit efficient, the image scale should be as small as possible, prefreably under $0''.5$/pixel. This scale does not seem very small, but if we take several (10 - 20) individual photos of a double to measure, the resolution of the result and its standard deviation decreases. A good way to improve image scale is to increase the focal length. For this purpose, a Barlow-lens may be used, or a focal extender sold for photographic purposes. I apply a 2x extender, with which the image scale value becomes $0''.31$/pixel. The area of sky covered in the images is thus $18' \times$ x$24'$, so in many cases a number of separate doubles can be recorded at the same time. The camera (without the lens) should be inserted into the telescope focuser with the required adapter. We may also need an adapter for the focal extender.

Calibration

The telescope-camera system must be calibrated. This means several steps. First we have to make the horizontal side of the camera and the sky declination circles parallel. We set a bright star in the camera finder, then move it across the image field by pressing the declinations button on the hand controller. If the star's movement is not parallel with the image's horizontal edge, we correct it by turning the camera adapter, and fix it in the right position. We don't need great accuracy here, as the remaining difference can be well measured later, and corrected when we get to the calculations. Good focusing is also essential, because due to the focal extender, the change in the distance between the telescope optics and the camera?s focal plane influences the image scale, which is another important part of the calibration. Defining the image scale can be done by calculations in the first round, and its exact value can be found by measuring the separation of known pairs. For good calibration, we should measure 10 - 20 doubles having very accurate separation value with the rough value of the image scale. Comparing the results with the known numbers, we can get to the exact value of the image scale in several steps. Later we will use this value for the measurements. It is very important to use the camera with a power adapter. On the one hand, the accumulator does not allow for work lasting several hours. On the other hand, when we change the accumulator, the camera can move from its calibrated position.

Taking photos

There is a simpler but tiring method, and a more complicated one which needs more technical equipment but is quicker, more effective and comfortable. I've used both in the past two years. For the simple method, we set the telescope to the required sky area with a hand controller, and record the images on the camera card. In this case the images can be checked on the camera's LCD display. We can also see it here, if the setting of the telescope's position is correct, and whether the chosen pair or pairs and stars are in the picture. Accurate focusing can also be done this way. In case of a larger Newton-telescope, using a ladder is inevitable (Figure 1). For this method, we need a remote switch. We set the required exposure time and continuous mode on the camera, and then by pressing the remote switch and setting it to 'lock' position, we can start photographing. Having taken the needed number of exposures, we turn off the remote switch, and set the telescope to the next target.

Fig. 17.2 The comfortable workshop in the telescope building

For the other method, both telescope and camera controlling can be carried out via a computer interface from a PC. Using a camera software, the images immediately load onto a PC (Figure 2). With this method, a comfortable workspace can be created. If we apply the GUIDE software(3) (computer star chart), we can set telescope mount positions through the program. We can also make the WDS Double Star Catalog(4), and databases selected from it appear in different colours and with different symbols. This way we may easily follow our own observation program, too. We can also make the sky area captured by the camera appear, thus four or even five pairs can be photographed at once in an area more crowded by doubles. With the help of the telescope control panel, we can carry out operations needed for positioning the telescope. (Figure 3).

With this method, even exposure can be contolled by a software. I use a freeware called COUNTDOWN(5). With a simple adapter, the program also takes photos through an RS-232 port. We may also create a list of tasks, defining how many images and of how long exposures should be made. The work process can be followed visually or through speakers. A software belonging to the camera downloads the images (USB port). This is immediately seen and can be checked on the computer screen. As I operate the camera and the telescope from two independent PCs, the image can immediately be compared with the Guide sky chart. Further computers with WIFI and internet connection also help to compare other images on the internet

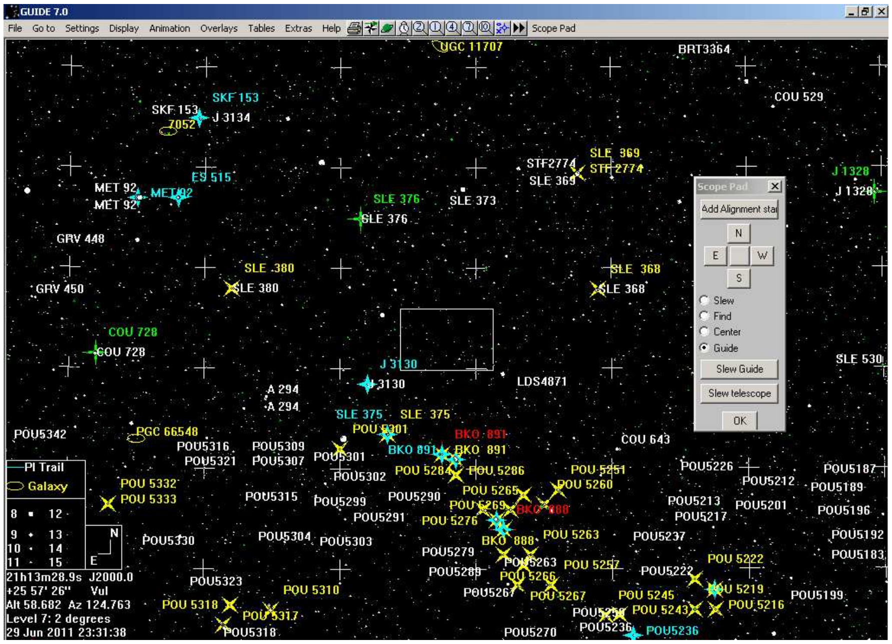

Fig. 17.3 Guide software with double stars and telescope control pad

(eg. Digital Sky Survey plates(6)). At times we must take photos necessary to define the camera position and the deviation from the declination circles. This is done by taking a series of pictures of long exposure time when the clock drive is switched off (10 - 15 images). The brighter stars draw horizontal or nearly horizontal trails. Later, by measuring and these trails, we get the deviation of the position angle.

Preparing the images

We must prepare the images for measuring the pairs on them. The applied exposure times (10 - 60sec) make it possible to photograph stars down to magnitude 14 or 15 in my living place, with medium level observation circumstances. Stacking is needed for measuring faint stars, and the images thus received show even the faintest ones. When dealing with too close pairs, we may need several image averages. This also helps our measurements. We need an image processing software, too, if the image file captured by the camera is not in the format that I need for the measurements. For most purposes, there is free software available, and PHOTOSHOP ELEMENTS 2.0(7) received with the camera is also very useful. For aligning, stacking and creating the image averages, I use ImagesPlus 1.7. (8). In my case the camera output file type is JPG, and the measurements are made on BMP type photos.

Measuring the photos

Measurements are done with one single program. REDUC(9), created by Florent Losse does all the required operations. It is enough to open all the photos of a given double, and mark the required components of the doubles one after the other, the software calculates to position angle and the separation values of the components, and their standard deviation for each photo. First of all, it is best to define the camera's position difference. We need to mark the beginning and the end points in the star trails, then by pressing the Drift Analysis function button, we get the Position angle difference (Figure 4).

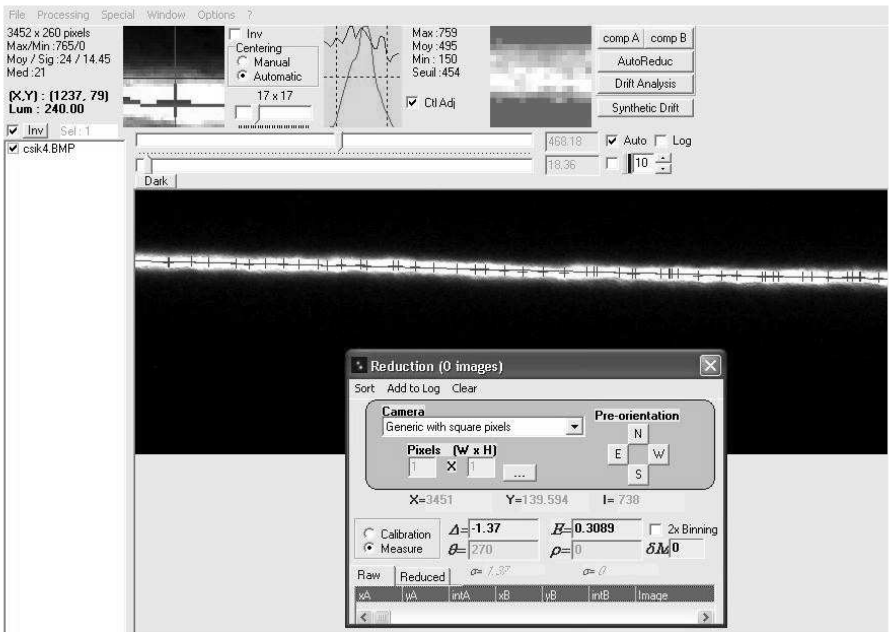

Fig. 17.4 Drift analysis in REDUC software

Putting this into the appropriate windows, together with the values we received for image scale during the calibration, we can start measuring the pairs. While measuring the image series belonging to the pair, the data of the lower quality images will be marked by different colours. We can delete pictures from among these, if we wish. (Figure 5). The program includes several further functions, now I wrote only about the basics. It can also be used for automatic measuring. What is more, by measuring a known pair, this program also gives the data needed for calibration. Since the software defines the star centroid to 0.001 pixels, if we measure several images of a pair, it becomes possible to receive results of smaller resolution than our system's image scale value. In my case this value is about $0''.1$, and the standard deviation is roughly of the same scale.

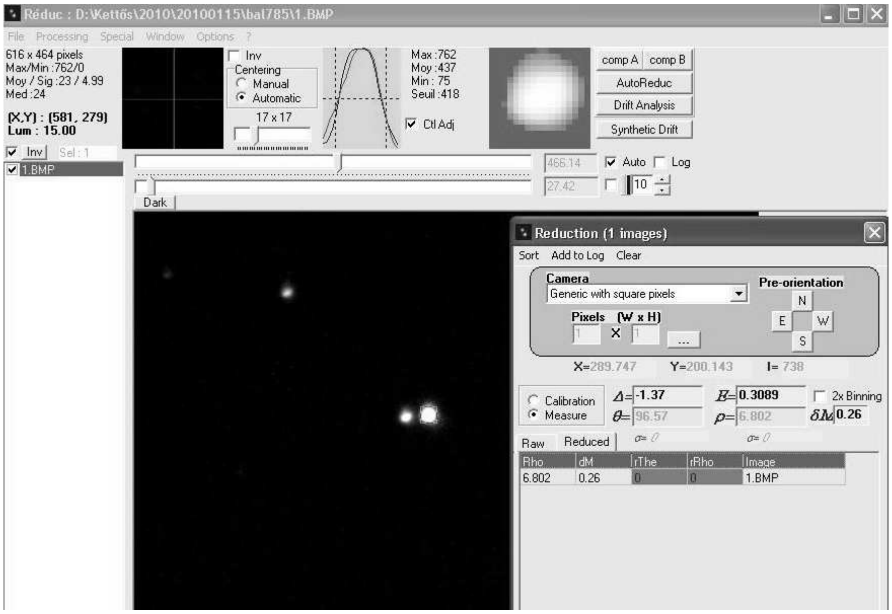

Fig. 17.5 Measuring a pair using REDUC software

Conclusion

With the above detailed equipment and method, it is very easy to measure magnitude 14 - 15 pairs of $>5''$ separation. In some cases, when seeing is better than the average, even doubles $\sim 2''$ can be measured. Although this is not accurate enough for measuring close binary pairs, it can be well used for identifying, checking and measuring USNO(10) neglected pairs.

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Chapter 18
How to measure the minima of eclipsing binaries; an amateur's experiences

Laurent Corp

Introduction

Eclipsing binaries are little studied by amateur astronomers: to order to observe them the keen amateur needs to become a photometrist. This chapter sets out to describe the various types of eclipsing binaries, how to predict the times of minima and the means of measurement - telescope, CCD camera photometric filters and computers - and finally the way in which the reductions are made. The last part explains light curves obtained in several different observing projects and a criticism of which is also given.

What is an eclipsing binary?

Variable stars in general can be placed into three categories: the pulsating stars, the cataclysmic systems, and the eclipsing binaries. In the latter case the variation in the light is due to binarity, with mutual eclipses by each component reducing the light of the system as a whole.

Eclipsing binaries in turn can be divided into three principle categories: the Algols (type EA), beta Lyrae stars (type EB) and W Ursae Majoris stars (type EW). In addition, there are sub-types which depend on the specification of the Roche Lobe. ? define Roche Lobe.

18.0.1 Algol stars (EA)

The primary minimum is well marked but the secondary minimum is much less obvious or almost undetectable. There are several thousand stars in this class.

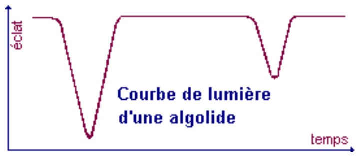

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Fig. 18.1 Light curve of an Algol system

18.0.2 Beta Lyrae stars (EB)

The primary eclipse is also well marked but in this case the secondary eclipse is almost as important as the primary. The light curve is xx due to the gravitational attraction on each star. This class contains only a few hundred examples. The stars are no longer spherical but deform into ellipsoids due to the intense mutual gravitational attraction. As the stars rotate the shape that they present to the observer varies, and the light from the system is constantly changing.

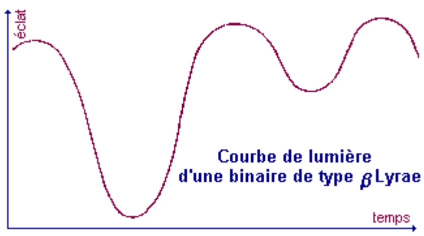

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Fig. 18.2 Light curve of a beta Lyrae star

18.0.3 W UMa (EW)

Primary minimum is almost identical to secondary minimum (see Figure 4)?? Here also there is an exchange of material between the stars line beta Lyrae. The period of the EW stars is often less than a day and can vary as a consequence of the mass exchange.

The orbital period of an eclipsing binary can be calculated by studying the light curve, and the relative size of each component (compared with the radius) can be observed by measuring the speed at which the luminosity of the more elongated star fades when the other star passes in front of it. If, in addition, the binary is also a spectroscopic system then the orbital elements can be found and the mass can be deduced relatively easily which means that the relative density of each of the stars should also be calculable.

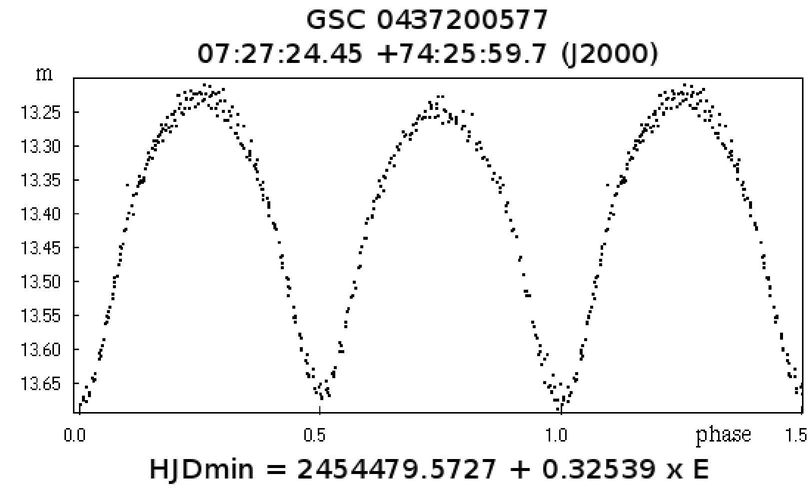

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Fig. 18.3 Light curve of a W UMa system

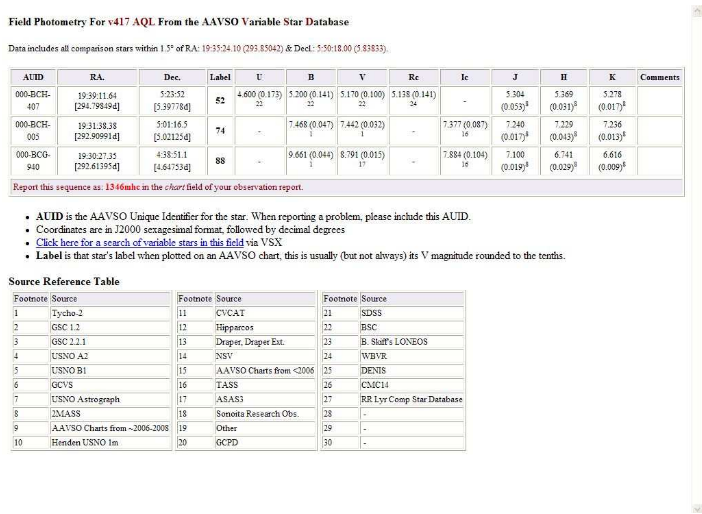
There is a website at `http://cosmion.net/software.ebs` which allows you to run a software simulation programme called Eclipsing Binary Simulator. The parameters of the binary system, such as mass, luminosity and distance can all be adjusted to reproduce various types of binary stars.

How is the minimum observed?

From the prediction of the time of minimum to the interpretation of the data, each stage is important and great care must be exercised. It is imperative to have data of the best quality available.

- How to observe the minima
  Predictions about times of minima are available from dedicated Internet sites whgich can supply tables of ephemerides for the help of specilaised computers for which the choice is small enough (see the box opposite).
  It is important to note that the times furnished by the different sites will be in Universal Time or local time. Certain times are calculated in geocentric time or heliocentric time. Now consider the predictions as an indication of the time of minimum. I strongly suggest using Universal Time from now if you haven?t already done so.
  The following site http://www.motl.cz/dmotl/predpovedi is managed by David Motl and you can use the predictions on the site the same if you do not have an available Internet connection (see Figure 4). It lists various parameters ? magni-

tudes, positions etc and different catalogues with lists of star to study. It is often very useful to make your own catalogues.



Field Photometry For v417 AQL From the AAVSO Variable Star Database

Data includes all comparison stars within 1.5° of RA: 19:35:24.10 (293.85042) & Decl.: 5:50:18.00 (5.83833).

AUID	RA.	Dec.	Label	U	B	V	Rc	Ic	J	H	K	Comments
000-BCH-407	19:39:11.64 [294.79849d]	5:23:52 [5.39778d]	**52**	4.600 (0.173) 22	5.200 (0.141) 22	5.170 (0.100) 22	5.138 (0.141) 24	-	5.304 (0.053)8	5.369 (0.031)8	5.278 (0.017)8	
000-BCH-005	19:31:38.38 [292.90991d]	5:01:16.5 [5.02125d]	**74**	-	7.468 (0.047) 1	7.442 (0.032) 1	-	7.377 (0.087) 16	7.240 (0.017)8	7.229 (0.043)8	7.236 (0.013)8	
000-BCG-940	19:30:27.35 [292.61395d]	4:38:51.1 [4.64753d]	**88**	-	9.661 (0.044) 1	8.791 (0.015) 17	-	7.884 (0.104) 16	7.100 (0.019)8	6.741 (0.029)8	6.616 (0.009)8	

Report this sequence as: **1346mhc** in the *chart* field of your observation report.

- **AUID** is the AAVSO Unique Identifier for the star. When reporting a problem, please include this AUID.
- Coordinates are in J2000 sexagesimal format, followed by decimal degrees
- Click here for a search of variable stars in this field via VSX
- **Label** is that star's label when plotted on an AAVSO chart, this is usually (but not always) its V magnitude rounded to the tenths.

Source Reference Table

Footnote	Source	Footnote	Source	Footnote	Source
1	Tycho-2	11	CVCAT	21	SDSS
2	GSC 1.2	12	Hipparcos	22	BSC
3	GSC 2.2.1	13	Draper, Draper Ext.	23	B. Skiff's LONEOS
4	USNO A2	14	NSV	24	WBVR
5	USNO B1	15	AAVSO Charts from <2006	25	DENIS
6	GCVS	16	TASS	26	CMC14
7	USNO Astrograph	17	ASAS3	27	RR Lyr Comp Star Database
8	2MASS	18	Sonoita Research Obs.	28	-
9	AAVSO Charts from ~2006-2008	19	Other	29	-
10	Henden USNO 1m	20	GCPD	30	-

!ht

Fig. 18.4 Light curve of a beta Lyrae star

Another downloadable site is that of Bob Nelson (`http:members.shaw.ca/bob.nelson/software1.htm`. The site is written by Bob Nelson another enthusiastic observer of these stars. You should note that the time s given by certain programs are deliberately approximate in order not to influence the observer.

Internet sites giving predictions of minima

`http://www/as/up/krakow.pl/epehem`- run by J. M. Kreiner of Mount Suhora Astronomical Observatory ? an outstation of Cracow Pedagogical University. This site offers times of primary and secondary minima for stars whose name and constellation are known.

`http://www.rollinghillsobs.org/perl/calcEBephem.pl`

Eclipsing binary eclipse generator. This site managed by Shaun Dvorak takes into account a number of catalogues and allows input of the observer?s latitude and longitude, the date and time of observation, maximum and minimum declinations and magnitudes.

`http://britastro.org/vss`

This site from the Variable Star Section of the British Astronomical Association also contains lists of stars to observer. The xxx is maintained by Des Loughney with whom I have collaborated on certain precise xxx and who observes with a DSLR in Scotland.

- How to choose a star to measure

  Choosing a star depends first of all on the amount of time available to the observer. So, if you have an observatory in your garden, setting up time will not be great as in the case where you have a portable telescope where it might take you a couple of hours to reach your observing site and another good hour to prepare for observing.

Choice will also depend on local conditions of light pollution, the experience of observation (to begin with it is better to choose stars that are easy to find and relatively bright, the performance of the available equipment (CCD, telescope, mounting) and time available. To get the most conclusive results I recommend that you to start observing 90 minutes before the minimum is predicted to occur and to continue for 90 minutes afterwards.

If you have never measured these types of star before I suggest that you choose those objects where the difference between maximum and minimum is more than 0.5 magnitude so that the light curve is easy to make. You can also help yourself by observing the star for a little while before comparing your results with those of others. When eventually you have made your choice of targets you will need the reference card and photometric table which can be obtained from the AAVSO website `http://www.aavso.org/observing/charts/vsp`

The charts show the name of the star, the card number, the field the orientation the magnitudes at maximum and minimum, the type of star and its spectral type. (see Fig 6).

The numbers indicate that these atrs are compariuson stars and each number represents the magnitude. Note that the numbers are not separated by commas or points in order to avoid confusion. The photometric chart (Fig x) indicates the brightness of the compariuson stars in the UBVRIJH and K bands. One other important thing which need to ve verified, either by using the AAVSO chart or a computer chart such as GUIDE 8m C2Am The Sky 6, for instance), is that the star being measured is not 'polluted' by neighouring stars otherwise you run the risk of measuring the target star as well as the neighbouring star.

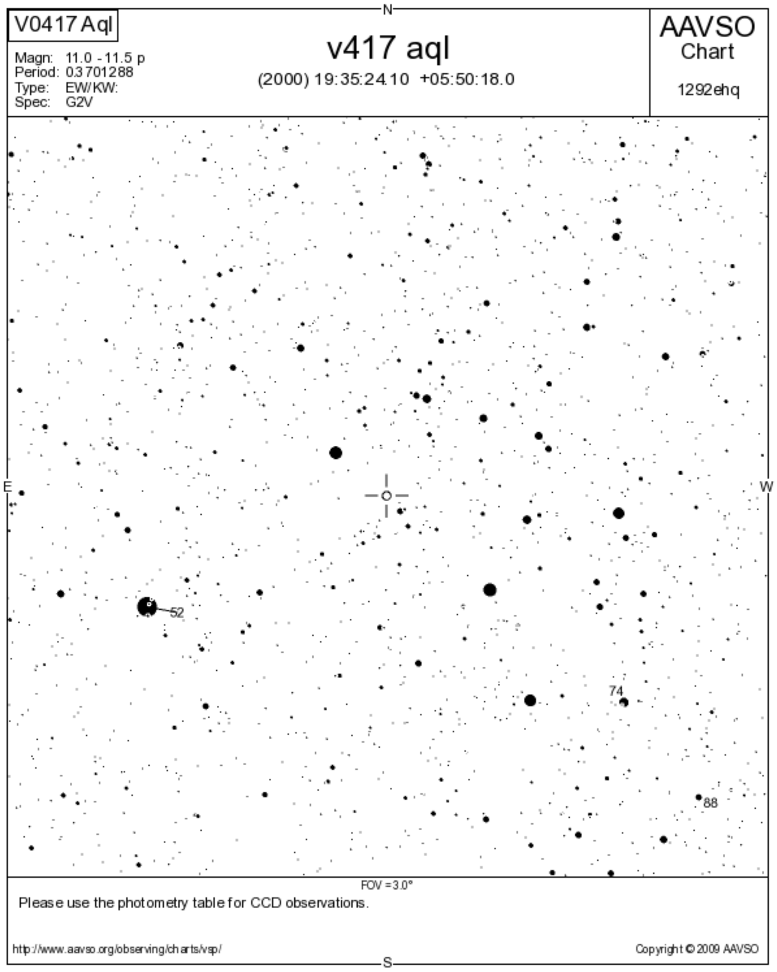
- Neglected targets?

  If you don't wish to observe known targets then there is a list of 141 whose minima are not known with certainty and some of these stars are quite bright (magnitude 5). Choose these targets only if you have some experience of the subject. You can download an Excel file from the following address
  `http://varsao.com.ar.eclipsing_binaries_observing_plan.htm`

How to choose the right equipment

I am not going to deal here with the details of setting up a telescope such as mounting, collimation, guiding and so on - you will need to master all this before you can succesfuly take star images

To take successfiul images is to produce a method which will allow you to get a photometric accuracy of about 0.01 magnitude, and only digital imaging techniques will allow you to attain that precision -0 either an APN or a CCD camera. As far as telescope optics are concerned a number of options are possible. A didtal camera on



!ht

Fig. 18.5 Field of V417 Aql (copyright AAVSO)

a tripod with a 200-mm telephoto lens can be employed. In this case the exposure time should not be longer than 2 seconds at a setting of ISO 800. One could equally use a CCD camera (Audine type or equivalent) with an objective of 135-mm aperture and a motorised mounting. You can find an interesting paper by Alain Klotz and Jean-Francois Le Borgne on the use of this type of set-up on the following site:

`www.ast.obsmip.fr.users/leborgne/gheos_circ/NC1105.pdf`

Even if this paper does deal mostly with RR Lyrae variables the method nevertheless shows what can be done with equipment which is a little bulky and of small aperture. It should be understood that all sorts of telescopes can be used - from Newtonians to Schmidt-Cassegrains and refractors) but the field covered by instrumenst of longer focal length becomes ever smaller and the comparison stars

Field Photometry For v417 AQL From the AAVSO Variable Star Database

Data includes all comparison stars within 1.5° of RA: 19:35:24.10 (293.85042) & Decl.: 5:50:18.00 (5.83833).

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000-BCG-940	19:30:27.35 [292.61395d]	4:38:51.1 [4.64753d]	**88**	-	9.661 (0.044) 1	8.791 (0.015) 17	-	7.884 (0.104) 16	7.100 (0.019)8	6.741 (0.029)8	6.616 (0.009)8	

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5	USNO B1	15	AAVSO Charts from <2006	25	DENIS
6	GCVS	16	TASS	26	CMC14
7	USNO Astrograph	17	ASAS3	27	RR Lyr Comp Star Database
8	2MASS	18	Sonoita Research Obs.	28	-
9	AAVSO Charts from ~2006-2008	19	Other	29	-
10	Henden USNO 1m	20	GCPD	30	-

!ht

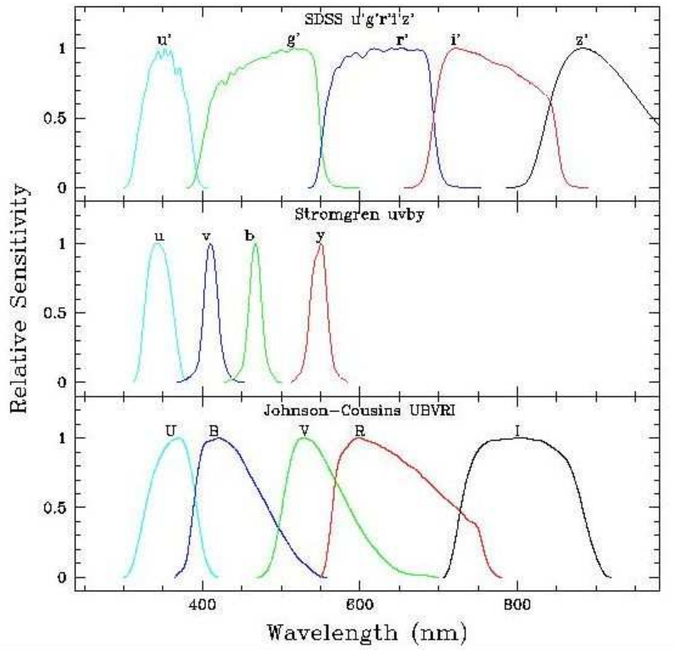
Fig. 18.6 Photometric table copyright AAVSO

are sometimes more difficult to identify. The use of larger apertures (such as the 60-cm at Pic-du-Midi which I use once a year) should be reserved for the measurement of faint stars.

If you are using a CCd camera then you need to ensure that the chip is monchrome, it is kept cooled electronoically and preferably has ab anti-blooming coat

Certain organsations require that observations be made using V abd R filters but there are several types of these filters and the ones you should use are those which are defined by the Johnson-Cousins system (see Fig. 7).

- My equipment and software
  The image above shows the camera that I use, and the two main objective lenses, the 35-mm and the 150-mm. A 15-cm sky baffle helps to keep out unwanted light. The filters have Johnson-Cousins response curves and work in the green and red. The camera is an SBIG-7 which is equipped with an Atik filter wheel with spaces for 5 filters and is controlled through a USB port by a program called CCDSOFT. A number of exposures are taken with each filter in turn and a star may be observed for a whole night in order to get ta sufficient number of images . The computer clock is kept on UT by a facility called Expert Mouse Clock. using this set-up and 90 second exposures, the magnitudes can be obtained with a scatter of 0.02 in R and 0.01 in V.
- My observation programme
  The main targets which I follow are the following stars: HD 23642 (an eclipsing binary in the Pleiades which is carried out in collaboration with David Valls-Gabaud at the University of Paris, OO Aql (see Fig. xx), V417 Aql, XY Leo and Y Leo.



!ht

Fig. 18.7 Spectral transmission of different filters

!ht

Fig. 18.8 50-mm lens for wide-field work such as eps Aur

!ht

Fig. 18.9 135-mm lens giving a 3 degree field

Secondly, stars in the RR Lyr class; these are studied using GEOS but I am looking at RR Lyrae itself with the TOMMIGO system.

Acquisition and xxx of the images

- acquisition
  On the ground, it is necessary to ensure that the image capture works properly, in other words the star images are not saturated. It is also necessary to obtain a sufficient signal to noise in the signal (SNR) The SNR that you obtain must be at least 50 and your software should be capable of displaying this value instantly. The following table lists some typical SNR values and the associated error in the observed magnitude

Table 18.1 Error in magnitude as a function of signal-to-noise ratio(SNR)

SNR	error
200	0.005
100	0.011
50	0.022
25	0.043
10	0.110
5	0.220

The software should also be able to care of filter changes automatically so that, for instance, V and R can be done alternatively, without manual intervention. If not, then you need to change your software so this can be done. Also, to be useful the PC needs to have an accurate value of UT. The internet contains several sites where this can be obtained. There is also the facility called Expert Mouse Clock. Xxxxx, you can carry out a series of exposures and I recommend say 300 continuous exposures of 30 seconds followed by 150 exposures at 30 seconds each spaced 30 seconds between each.

Depending on the season and the target selected, you should be able to make between one and three sets of observations on a single night. The final quality of the data will depend on quality and quantity. Some professional astronomers would like the whole light curve and not just the minimum and so you should have only one aim ? one star each night and on following nights if necessary.

It goes without saying that to get precise data, it is necessary to get good calibration frames offset (or bias frames), darks and flats. Preliminary treatment of the raw data conforms to certain rules and ?cosmetic? treatment of the raw data is not done, especially ‘touching-up? the images to make them flatter ? the final results will be misleading.

Calibrations have an effect on the reduced data and it is vital that you are aware of this. The page that you can download from the AAVSO site contains comparison star magnitudes which you can use to reduce your variable. You ?before extracting photometric data from your images.

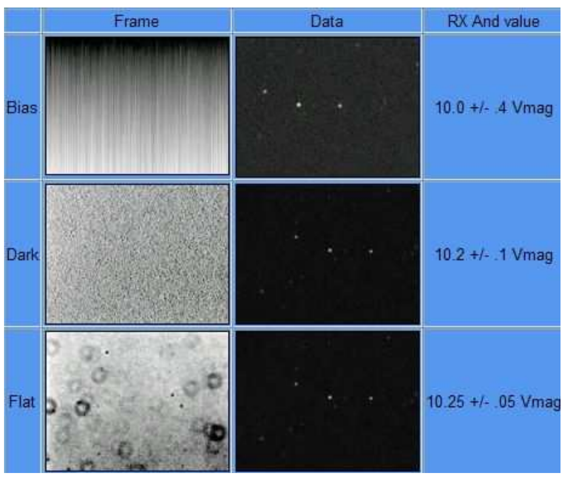
!ht 

Fig. 18.10 The effect of the calibrations on the images obtained

Here the method used is the same - that of differential photometry - the flux from the variable is compared to that from a nearby comparison star. Here is some advice: Use the comparison stars whose apparent magnitude and colour is nearest to that of the target star. Pick a B-V or V-R colour index which is most suited to the filters being used. Check, using a test star that the reference star magnitudes are stable with time!

The light flux from the star in the chosen camera window can be either circular or elliptical. If your camera does not have square pixels, do not transform rectangular pixels into square pixels. Comparing the variable to the nearest neighbouring stars is similar to the technique used by visual observers. The choice of diameters for the circle is very important.

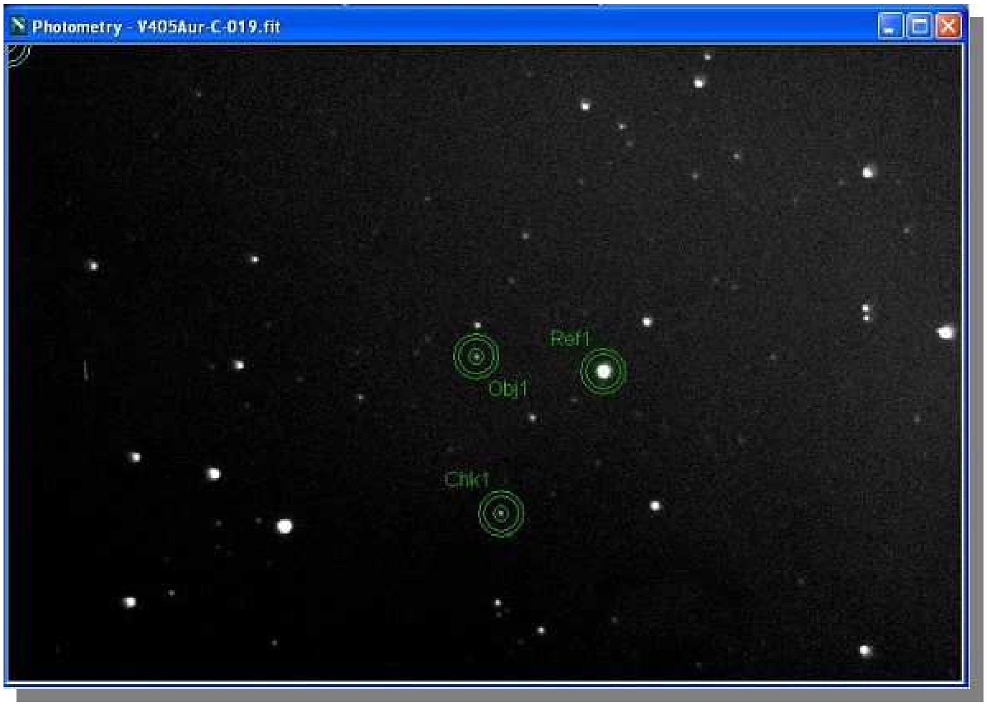


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Fig. 18.11 Light curve of a beta Lyrae star

In figure x (above) the circles correspond to three objects: Obj1 is the target being observed. Chk1 is the comparison star which has a similar colour index. Ref1; is the reference star. The circle diameters t use for each of these objects is defined as follows. The smallest circle has a diameter 2 X FWHM, the next smallest is 3 x FWHM and the largest circle is 5 x FWHM

- Sending the data

  The form on which you send the data will depend on the organisation it is being sent to and I can monly suggest that you look at their website to see what is required.

  ??..comparison stars which you can use to reduce the data on your variable. If you want to use the best data then use the photometric table.
- Determination of the time of minimum

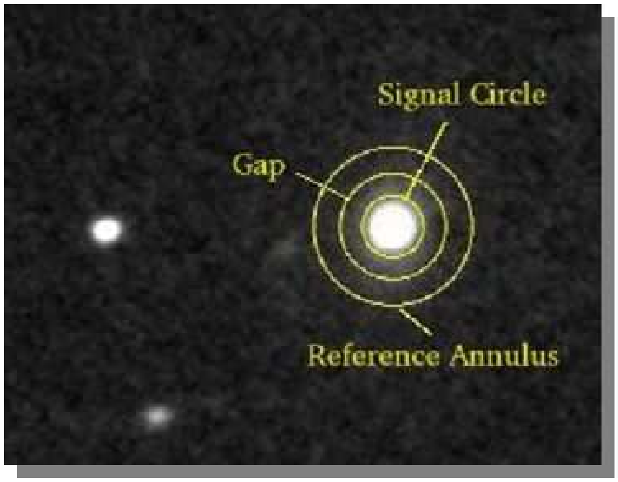

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Fig. 18.12 Light curve of a beta Lyrae star

This is not something that you need do yourself. If you send the data to a responsible organisation, they will arrange for an experienced astronomer to determine the time of minimum from your data. It is however alwats interesting to verify results. You should check that the data you have sent is acceptable before spending more hours obtaining new data. Software which is either free or paid for can help you to interpret your measures and get the time of minimum - see the list below for instance.

When the time of minimum is known the Observed - Calculated residual can be determined and then we will know if the period varies with time.

18.1 Some light curves

Use reference stars whose magnitudes and colour index are close to that of the variable Choose an almost identical B-V or V-R colour index depending on the filters used. Be certain to check that your reference stars are stable with time by checking with a test star.

Software to reduce data:

MINIMA 2.5 - free from Bob Nelson and avilabale on http://members.shaw.ca/bob.nelson/software1.htm allows the user to determine the time of period using 6 methods.

TOMCAT - free from Bob Nelson and available on http://members.shaw.ca/bob.nelson/software1.htm which alows the time of minimum to be determined from the calculated period

PERIOD SEARCHPERIOD SEARCH - free from Bob Nelson and available from: http://members.shaw.ca/bob.nelson/software1.htm calculates the period by examining a portion of the light curve.

PHOEBE(PHysics Of Eclipsing BinariEs), free and available from: http://phoebe.fiz.unilj.si/?q=node/21 donne une modlisation 3D du système mesur.

PERANSO - by payment to Tonny Vanmunster and avilable on sur http://www.peranso.com/

BINARY MAKER by payment to Contact Software at http://www.binarymaker.com

18.2 Some typical light curves

- OO Aql RA: 19h 48m 13.0s Dec: 9 18? 30?? JD0: 54335.36020 Priode: 0.5067885

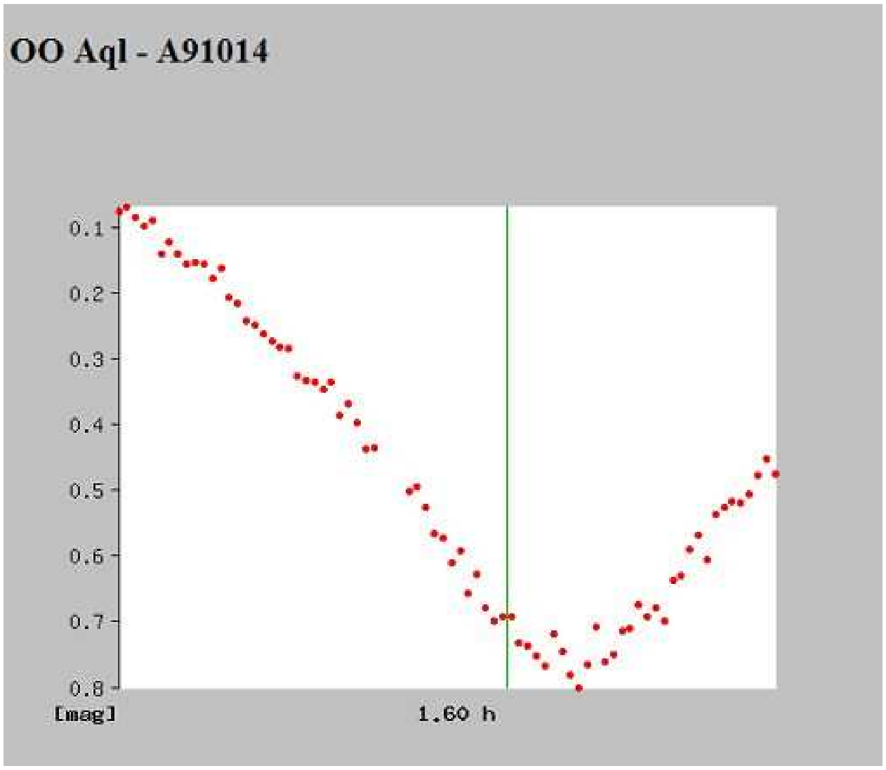
!ht 

Fig. 18.13 OO Aql - RA: 18 38 13 Dec: +09 18 30. JD0: 54335.36020. Period: 0.5067885 days. 75 images from 2009 Oct 14 showing evidence for a time-kag between the predicted minimum (shown by the vertical line) and the observed minimum

Fig 10 shows the O-C curve of the star OO Aql and we can see very clearly that the residual is increasing from year to year and this rtells us that material is being transfreed from one star to another.

- RW CMi

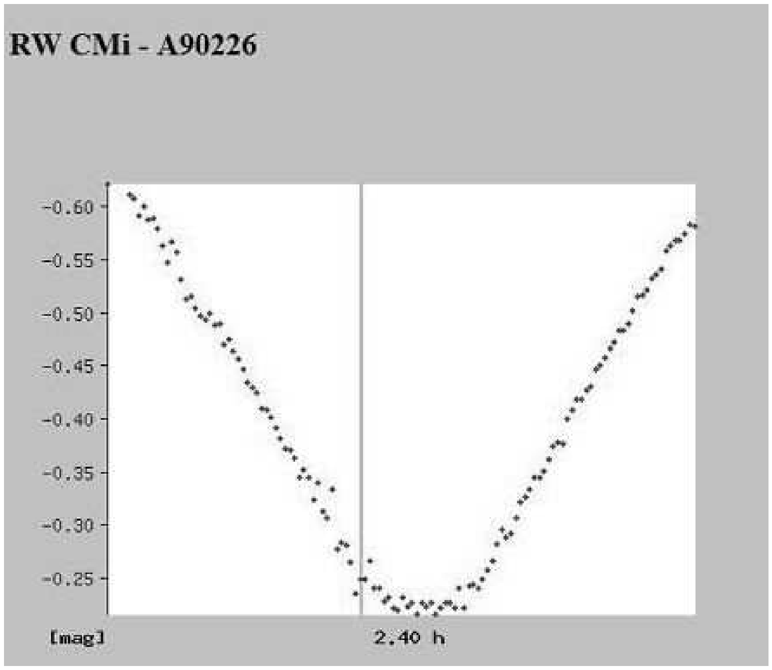
!ht 

Fig. 18.14 RW Cmi - RA: 7h 20m.0 +02 32 00, JD0,= 50837.61. Period: 6.083282 hours. Range: 13.2-14.0

In RW CMi a significant time lag ca be seen between the therotical time of minimum (represeneted by the vertical line) and that observed. Note also that the minimum lasts sveral minutes. These observations were made with the 60-cm at Pic-du-Midi (http://astrosurf.com/60) during an observational campaign in 2009 February.

- GU Boo
  There is, however, no time lag between theory and observation in the system of GU Boo as can be seen in Fig xx. Note especially the speed at which minimum occurs. These measures were also taken at Pic-du-Midi in 2009 February using the 60-cm telescope.

Star	Date	Number of measures	Predicted time of minimum	Measured time of minimum	Difference	Notes
RW CMi	2009 Feb 26	122	22:19	22:33	14	Needs re-observing
GU Boo	2009 Feb 26	120	01:32	01:32		

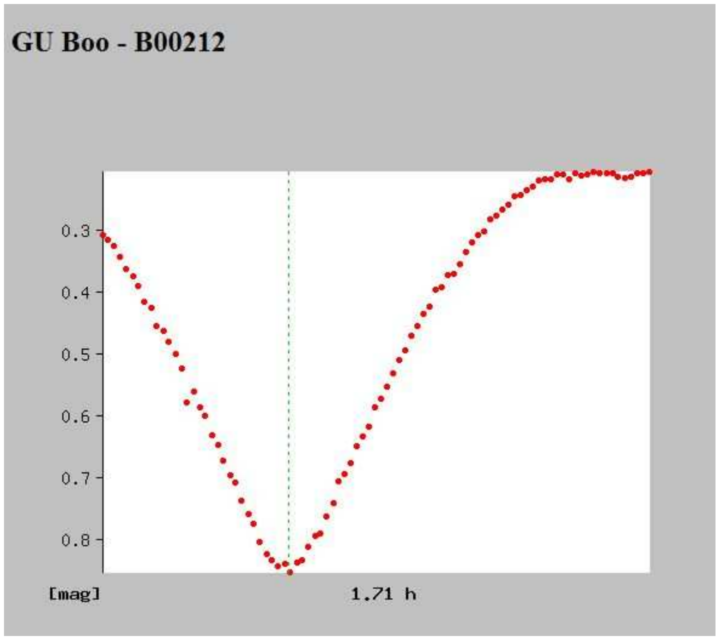
!ht 

Fig. 18.15 GU Boo - RA: 15h 21m 55s +33 56 06, JD0,= 52723.981 Period: 0.4887300 hours. Range: 13.7-14.4

18.3 Conclusion

In these few lines, I have tried to sum up what you will need to do in order to help the astronomical community in better understanding these types of stars. This is a testing activity which requires a lot of time and trouble in perfecting a technique before getting acceptable results. Good luck with your observations, and clear skies!

References

Expert mouse clock : http://www.gude.info/index.php?lng=1&section=products&product=emcusb&PHPSESSID=1301b
af6557da4dcf66c2dc8e26d2b95

AAVSO American Association of Variable Star Observers (database of light curves, advice, discussion groups, etc.)
http://www.aavso.org (this is the best site in my opinion)

CCD Observing Manual http://www.aavso.org/ccd-observing-manual

Variable Stars South: http://www.varstars.org/ Check the newsletters of May, August, November 2009, February and May 2010

A Guide to Photometry by W. Romanishin (Oklahoma University.):

http://observatory.ou.edu/book2513.html
Starizona's Guide to CCD Imaging http://starizona.com/acb/ccd/ccd.aspx
CCD : Astuces of observations by Bruce Gary:
http://reductionism.net.seanic.net/ObservingTips/ObsgTips.html
Astronomical institute, Academy of Sciences of the Czech Republic, Ondrejov
http://nyx.asu.cas.cz/dbvar/descr.phtml
Howell, Steve B., 2006, Handbook of CCD Astronomy, 2nd Edition (Cambridge University.Press)
Berry, Richard and Burnell, James, 2005, The Handbook of Astronomical Image Processing (Richmond, VA: Willman-Bell)
Henden, Arne and Kaitchuck, Ronald, 1990, Astronomical Photometry (Richmond, VA: Willman-Bell)
Brian D. Warner Lightcurve Photometry and Analysis
Well-written book - all you need to knwopa bout obtaining, treating and analyzing data.
W. Romanishin Universitiy of Oklahoma, An Introduction to Astronomical Photometry Using CCDs
A 175 page book based on a university course. At acceptable level without too much mathematics and easy to read. http://observatory.ou.edu/wrccd22oct06.pdf
http://www.astrosurf.com/luxorion/Documents/evolstarbmauclaire.pdf
(43 pages in French about the life of stars
Nelson, R.H. website: http://members.shaw.ca/bob.nelson
OEJV: http://var.astro.cz/oejv/
SAS : http://www.socastrosi.org - conference reports to download

Databases

ADS: http://adsabs.harvard.edu/article_service.html?nosetcookie=1

BBSAG: http://www.astroinfo.org/calsky/Deep-Sky/index.html/8/3

BAV: http://www.bav-astro.de/LkDB/index.php?lang=en
CALEB: http://ebola.eastern.edu/
Crakow Atlas of EBs: http://www.as.ap.krakow.pl/o-c/cont.html

EB Minima dB: http://www.oa.uj.edu.pl/ktt/krttk_dn.html
GCVS: http://www.sai.msu.su/groups/cluster/gcvs/cgi-bin/search.htm

IBVS: http://www.konkoly.hu/IBVS/issues.html
SIMBAD (Harvard): http://simbad.harvard.edu/simbad/sim-fid
SIMBAD (Strasbourg): http://simbad.u-strasbg.fr/simbad/sim-fid

Chapter 19
Occultations

Graham Appleby

19.1 Introduction

One of the difficulties of observing and accurately measuring the relative positions and magnitudes of components of double stars is their mutual interference. Either one component is much brighter than the other, or the apparent separation between them is too small to be resolved by the optical system, particularly in the presence of distortion by the Earth's atmosphere. Ideally the components could be obscured one after the other to allow unambiguous observation of the companion as well as an estimate of the separation between them. This in essence is the principle behind application of the occultation technique to the observation of double stars.

Now, the Moon in its orbit around the Earth-Moon barycentre frequently obscures (occults) stars. As a consequence both of the inclination of the Moon's orbit with respect to the ecliptic and the precession along the ecliptic of the nodes of the Moon's orbit, all the stars in a belt of some 10 degrees around that plain are occulted at some time during a period of about nine years. Among these are the bright stars Aldebaran, Regulus, Spica, and Antares and the star clusters Pleiades, Hyades and Praesepe. Since the Moon always moves eastward, an occulted star disappears at the Moon's eastern limb and reappears at its western limb. The phenomena can be best observed at the dark limb of the Moon, so in general disappearances are observed each month during the two weeks between New and Full Moon, and reappearances during the following two weeks. Since the invention of the telescope, professional and amateur observers using a variety of techniques and instrumentation have recorded many thousands of timed observations of lunar occultations. Analyses of these observations have addressed such problems as improving the dynamical theory of the motion of the Moon, investigating the variable rate of rotation of the Earth, determining stellar reference frame anomalies, measuring apparent stellar diameters and parameters in multiple star systems. It is the last two items that are of particular relevance to the subject of this chapter, but in the following sections the power of the occultation technique will be examined with reference to all of these applications.

19.2 Observation

The scientific observation of an occultation involves accurately recording the instant at which the star disappears behind or reappears from behind the lunar limb. In all but occultations of the brightest stars, telescopic or binocular aid is essential for making an accurate measurement; as the Moon approaches the star the glare from the sunlit part of the disk totally overwhelms the light from the star. By using optical aid to restrict the field of view, in most cases the star can clearly be seen at the moment of occultation.

The Moon orbits the Earth in approximately 28 days, which leads to an average Easterly motion against the background of stars at a rate of 0.5 arc-seconds per second of time. If the instant of occultation can be estimated to a precision of 0.1s, then the relative position of the lunar limb and the star is known at that instant to a precision of 0.05 arc-seconds. The analysis of such observations proceeds by the computation both of the position of the center of the Moon at that instant by interpolation in a lunar ephemeris and a precise knowledge of the position of the observer on the Earth's surface, and the position of the star taken from an appropriate star catalogue. Also, the lunar limb is not smooth; it has roughness of apparent angular extent ~ 2 arc-seconds, caused by variations in the level of the lunar terrain along the line of sight from star to observer. From this information, the apparent distance of the star from the lunar limb at the instant of recorded occultation may be calculated. Almost certainly, the computation will imply that the star should have been occulted at a slightly different time than that recorded by the observer. The reasons for the discrepancy will include errors in all the assumptions made to compute the circumstances of the occultation, such as errors in the position of the star given in the catalogue, errors in the lunar ephemeris and in the charts used to derive level of the lunar terrain. A further correction will be attributable to the method used to make the observation. No matter how well prepared and experienced the observer, there is inevitably a time delay between the instant that the observer perceives and then records the event. If a stopwatch is used to record the event, it has been estimated (1) that this delay, or personal equation, is on average about 0.3 seconds for a disappearance and 0.5 seconds for reappearance, the larger value for the latter being due to the intrinsic 'surprise' element of this type of event. Another recording technique in common use is the so-called eye-and-ear method; the observer listens to an audible one-second time signal whilst concentrating on making the observation, then mentally estimates the time of the event as a fractional part of a second. Results of analyses (1) suggest that this method is essentially free from personal equation effects, with observers achieving measurement precisions of about 0.1 seconds. A far more accurate technique used principally at professional observatories is to record the occultation events electronically. A photo-multiplier is used to count individual photons reaching the telescope from the star, and the counts are integrated over contiguous, short time intervals, of duration say one milli-second. The resulting light curve can then be analysed to determine among other quantities the instant of occultation with precision close to one milli-second.

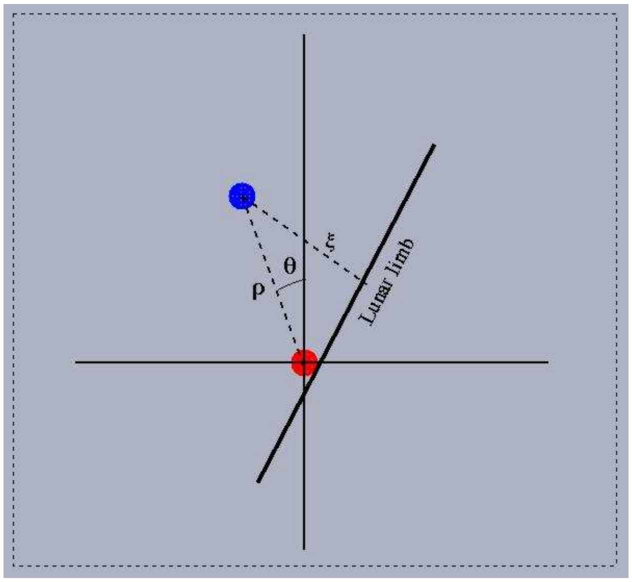


Fig. 19.1 Schematic of an occultation of a double star.; the components are separated by separtion ρ in angular position θ. The projected separation ξ mat be estimated from the time difference between the two occultation events

19.3 Double stars

These then are the techniques of lunar occultation observation, where the star being occulted is a single star. If the star is in fact a double or a binary system, the intrinsic spatial resolution of the technique can be exploited to determine several useful parameters, depending upon the observing method. If the times of occultation of each of the components are measured by one of the techniques discussed above, then the separation of the components ρ, projected onto the apparent direction of motion of the Moon, can be determined simply from x= L_t.r, where L_t is the difference in time between the two events, and r is the rate of motion of the Moon. Now also, x=ρ.cos(θ-f), where ρ, θ are respectively the angular separation and position angle of the double star components, and j is the position angle of the occultation event on the lunar limb.

Provided that the personal equation effects discussed above are the same for each of the two events, then the accuracy of determination of x is limited only by the resolution of the timing technique. If a series of observations of the same double star is carried out either from different locations, or over a period of time, such that a range of values of f is achieved, then it would be possible to carry out a solution for the values of ρ and θ.

19.4 Visual Observations

This discussion implies that both components of the system are visually resolved during the occultation; if the components are too close together to be resolved, then the observed effect has been determined (2) to depend both on the apparent separation of the components and on their relative brightness. An analysis of a large number of occultation observations that had been made over some 35 years showed that for more than 420 of these observations the observer reported an anomalous event. The observers recorded these occultation events as not to have occurred instantaneously, to have 'faded' either smoothly or in a stepwise fashion. For 160 of these events, it was found during the analysis that the 140 stars involved were in fact close doubles, many of which had been discovered by other techniques at later dates. For many of these known double and binary systems their separations and position angles were sufficiently well known to enable a calculation of the expected time intervals between the occultations of the two components, and whether the brighter or fainter component was occulted first. Intuitively it may be expected that for components of similar magnitude and for close doubles where the two occultations follow in rapid succession, the event may appear gradual, taking a slightly longer time to complete than the more normal instantaneous disappearance or reappearance. However, for wider pairs, or where the difference in magnitude of the components is large, the event might be expected to appear more dramatic, with a clear drop or step in brightness after the occultation of the first component. This expectation is born out by the data, as shown in Figure 1, where for each of the 160 events the calculated event duration is plotted against the computed brightness-change after the occultation of the first component. The observers' comments from the original observation records have been interpreted as either 'gradual' or 'step' event, and used to code the observation symbol on the plot. It is clearly seen that the observations are split into two classes according to whether there was a large change in brightness or long duration (step observed), or subtle change in brightness or short duration (gradual event). These results may then be used as a rough guide to interpret further visual observations of occultations, where a non-instantaneous event is observed.

The analysis (2) discussed above concluded that a further 130 stars from Robertson's Zodiacal catalogue (3) were likely close doubles and would warrant closer study by say speckle interferometry, or high-speed photometric observation of future lunar occultations. At least one star from the target list given in (2) has been confirmed as double as a result of this work.

19.5 Photoelectric Observations

Naturally, if the photoelectric method is used to observe occultations, detection of much closer pairs should be possible. For high-speed photometry with millisecond (ms) resolution, separations of a few milliarc-seconds (mas) should be detectable. However, such observations are not straightforward to analyse, since diffraction and

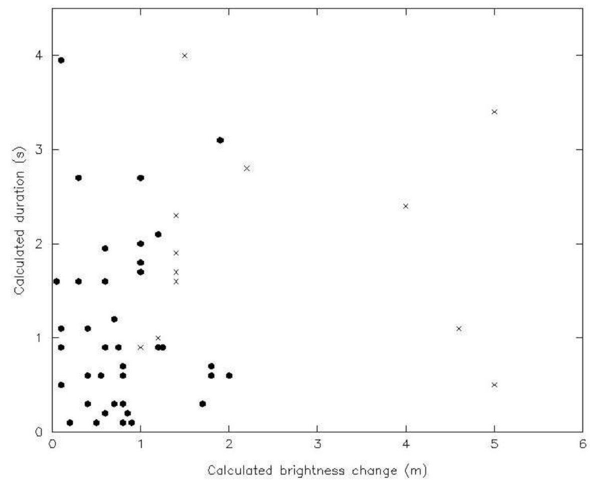


Fig. 19.2 Observed events for known double stars as a functioon of calculated duration and brightness change; circle - 'gradual', cross = 'step'

Table 19.1 Liust of stars that have been observed to fade on at least three occasions. For an 0n-line catalogue of stars which can be occulted by the Moon see the website of Paul Schytler(7)

HD	ZC	SAO	Mv
16302	387	75476	6.9
22017	516	93487	7.3
23288	536	76126	5.4
27934	656	76601	4.4
65736	1203	97468	7.1
88802	1500	118181	8.1
89307	1506	99049	7.1
120235	1978	139559	6.6

stellar diameter effects dominate the high-resolution light-curves. During an occultation event, a series of alternating bright and dark fringes, the Fresnel zones, are generated and sweep across the observer during an interval of some 40ms. The first zone, across which the intensity of the light drops smoothly to zero from a value 1.4 times its pre-occultation level, is about 13m wide on the surface of the Earth and subtends an angle of about 8mas at the distance of the Moon. Stars with apparent angular diameter less than about 1mas will generate a diffraction pattern close to that expected from a point source. Those with diameters significantly greater than this will create patterns that can be considered as the sum of a series of point source diffraction patterns displaced in time relative to each other (4). Thus for high-speed measurement of an occultation event where the diffraction pattern is sampled say at a resolution of 1ms, the characteristics of the resulting light-curve will depend

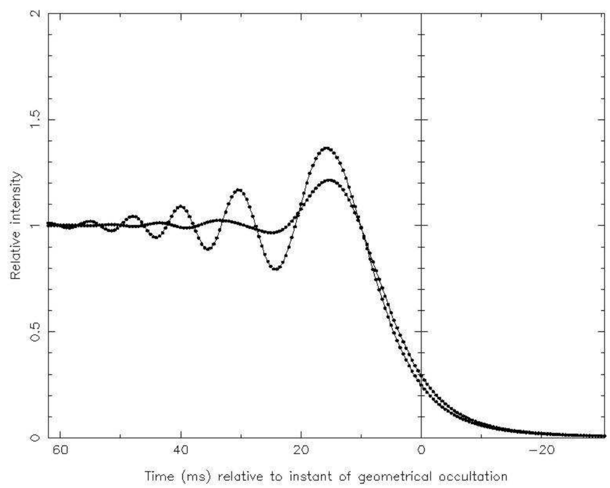


Fig. 19.3 Theoretical light curves for occultation of a point source (dashed curve) and for a star of angular diameter 6 mas (solid curve)

upon the diameter of the star. This effect is illustrated in Figure 2 for a point source and for stars of angular diameter 10 and 40mas. In fact, the light-curves illustrated here have been further modified from the purely theoretical ones to take account of finite bandwidth of the detector system and non-zero telescope aperture (modelled as 50cm).

The variation apparent in Figure 2 of the shape of the light curve as a function of stellar angular diameter can of course be exploited in the analysis of observed light curves; both the precise time of occultation and the stellar diameter may be estimated by non-linear least squares methods. An initial estimate of the diameter is made, perhaps from previous observations or from theoretical considerations based upon the star's spectral characteristic (5) and used to compute an approximate light curve. This is then compared point-by-point with the observed light curve and the differences used to solve for corrections to the initial estimate. The process is repeated until convergence is reached and depending upon the quality and signal-to-noise ratio of the data, precisions of better than 1mas may be achieved. In practice several other parameters are solved simultaneously with stellar diameter, such as an estimate of the brightness of the star, the background noise and rate of motion of the lunar limb. A large number of stellar diameter measurements has been obtained by this method and published in the astronomical literature.

The method can readily be used for the analysis and discovery of close double stars. If evidence of duplicity is suspected in an observed light curve, the modeling process is extended in order to compute a theoretical curve by summing two such curves displaced in time and amplitude by the initial estimates of component separation and brightness and lunar limb-rate. The fitting process is identical to the single-star case, except that now two diameters may be estimated along with the parameters of the double star system. The results of such analyses are of course the same as for the visual observation method, in the sense that only the component of the double star separation in the direction of motion of the lunar limb is determined from a single observation. However, separations as small as a few mas are detectable.

19.6 Summary

The occultation technique is seen to be a valuable tool for serendipitous discovery of double stars, where visual observation can be valuable. Accurate timing of the separate events can lead to measurement of minimum separations at sub-100 mas levels of precision, as well as estimates of the relative brightness of the components. High-speed photometric observations are capable of mas-level observation.

19.7 References

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Chapter 20
What the amateur can contribute

20.1 Introduction

In this book we have been looking at various ways in which the relative positions and brightnesses of double stars can be measured in such a way as to contribute to the general knowledge of these objects. The main areas of opportunity can be summed up as follows:

Graticle and CCD observations of faint, wide pairs

There is no doubt that there are large numbers of relatively wide and faint systems for which little astrometry and photometry exists. The USNO have recently published on their web site a list of more than 6,000 pairs which have yet to be confirmed as doubles or which have been unduly neglected. These pairs are all wider than 3 arc seconds and are relatively faint but could be observed satisfactorily with a medium aperture and a graticule micrometer (see Chapter 12 and the work by Harshaw (1). These stars would be also be ideally suited to CCD astrometry even with a moderate telescope and a commercially available CCD camera. Chapter 16, written by Doug West, indicates how this can be achieved. The list of neglected pairs can also be found on the CD-ROM.

Micrometer measures of long period binaries

Many of the brightest binaries such as Castor, γ Leo and 61 Cygni have orbits graded as 4 or 5. These pairs will benefit from continual monitoring and are easy with small telescopes and micrometers. The frequency of observation should be matched to the apparent motion in the orbit, so in the case of Castor, for instance, annual means at the present time still show significant differences and should be continued for some years yet. For γ Leo, however, motion is currently very slow and means could be taken every 5 years or even 10 years without detriment. The important point is that the measures should be made since it is by no means clear that the professional community will be doing it. As techniques become more sophisticated, the close and rapid binaries are becoming the focus of attention leaving the wide visual pairs virtually unmeasured.

For pairs wider than about 10 arc seconds then most of these systems are probably optical pairs and occasional measures can serve to check on the proper motions of the component stars. It is even possible to find errors in the Hipparcos Catalogue, as Jean-Franois Courtot has done with his 21-cm reflector and filar micrometer (2).

Relative positions of faint stars from Sky Surveys

Vast amounts of untapped data on wide pairs lie in the various Sky Surveys taken with the world's largest Schmidt telescopes at ESO, Siding Spring and Palomar Mountain. What is more the data now encompasses several wavelength bands and epochs. A determined individual, such as Domenico Gellera of Lodi, Italy, who has built and used his own measuring machine (3) can make substantial contributions because many of the pairs on these charts are not only unmeasured but uncatalogued. Sr Gellera has shown that it is possible to measure pairs as close as 5 arc seconds using a microscope fixed to a two-axis measuring machine. He has made over a thousand measures of the pairs of Pourteau and in most cases these are the first and only measures since the original catalogue was compiled from Astrographic zone plates (4,5) . This work was done from photographic prints of the Palomar Schmidt survey and a single print typically contains hundreds of pairs. In collaboration with Willem Luyten he used his measuring machine to measure the relative positions of pairs of white dwarfs (6).

It is not even necessary to have a measuring machine to extract data from the Sky Surveys. The USNO have created a number of large catalogues the biggest of which (the A2.0 catalogue) is the result of scanning Schmidt plates using the PMM machine at Flagstaff Station in Arizona. The result is a catalogue with 526 million stars down to magnitude 19 or so and distributed on 10 CD-ROM's. A smaller alternative is the SA2.0, with 55 million stars now only available by ftp from the USNO site(7) (The UCAC is a more recent and more accurate catalogue based on Tycho-2 and USNA2.0 which contains 27 million stars between mags 8 - 16 in the southern hemisphere. Pairs and multiple stars closer than 3 arc seconds are not listed. It is not quite complete covering about 80the astrograph used being relocated in the northern hemisphere. The sky has now been observed as far north as +45 and the results will appear in UCAC2 in 2003 or so. UCAC gives positions good to 0.02 arc seconds between mags 9 and 14 and 0.07 arc seconds at mag 16. The mean epoch is between 1998.0 and 1999.9. The data is made available in a form suitable for Unix/Linux, MAC or MS Windows.)

An alternative is to use facilities such as ALADIN on the SIMBAD web site. A description on how to use this facility is given by West (8).

Visual confirmation of pairs in the WDS

There are several thousand pairs in the WDS which have only one observation - that of the discoverer and the WDS project team have requested confirming observations. There is a useful opportunity here to contribute by checking these pairs and seeing, firstly if they exist, and secondly to make an estimate of the relative positions and magnitudes to see if any have moved significantly since discovery. Many of these pairs would be suitable for both visual and CCD imaging or could be located on the various Sky Surveys. The list can be found on the USNO website.

Photometry

Perhaps the greatest lacuna in the WDS is the lack of good photometry for many of the wider systems. With a CCD camera, it is possible to measure magnitudes for double stars in some or all of the standard wavebands such as B,V,R and I. (U can be attempted if the CCD front window is coated with a layer of ultraviolet transmitting material but this can be quite expensive). Colours are defined such as B-V, V-R and R-I and are easily calculated from the individual magnitudes in those particular wavebands. Required filters can be made up from commercially available glass such as that made by Schott. For further information see the articles by P. Boltwood (9, 10) (contact e-mail: boltwood@fernbank.com)

Doubtless, there are many variable components yet to be discovered and in the case of double stars the great advantage is that there is a built-in comparison already available for doing differential photometry.

Lunar occultation observations

Graham Appleby has already described the use of lunar occultations to investigate the duplicity of previously single stars in Chapter 18. Further information on all aspects of lunar occultation work can be obtained from the International Occultation Timing Association at http://www.lunar-occultations.com/iota/iotandx.htm

Use of large refractors

It is certainly true that many of the large refractors originally designed to do micrometer work on close binaries are not currently being used for this purpose and some are almost unused, such as the great 26.5-inch refractor at Johannesburg (Figure 19.1). Some are available for research by amateur observers who have a serious programme of measurement to carry out, in particular, the 50 and 76-cm refractors at Nice, as described in Chapter 21.

Refractors of 12-inch to 15-inches in aperture, of which there are many still in working order, particularly in the USA could be employed for measuring some of the new Hipparcos and Tycho pairs. The long focal lengths of many would make them suitable for using a CCD for astrometry and photometry of faint pairs.

Fig. 19.1 The 26.5-inch (67-cm) Innes refractor at Johannesburg, pictured in 1982. (Bob Argyle)

Calculation of orbits

We always hope that the end product of all our hard-earned micrometer measures on a particular system will be the derivation of an orbit from the apparent ellipse and an idea of the total mass in a binary system. It may not be in our lifetime but there is a certain satisfaction from putting down a database of reliable measures that some future researcher will be able to use. Alternatively it is possible to do orbital analysis on systems which have sufficient observations to cover an arc which will allow a good estimate of the apparent ellipse to be made.

Andreas Alzner has gone into the details of orbital analysis in Chapters 7 and 8. Not only professionals, but also skilled and mathematically-minded amateurs, like René Manté in France, regularly publish useful new orbital elements (cf. IAU Commission 26 Circulars). It is certainly a challenging occupation and needs a good appreciation of the problems which are posed. Now comes the awful warning. There have been some very bad orbits appearing in print. One had the companion going in the wrong direction and another used an apparent arc of 3 degrees to calculate an orbit of several thousand years and quoted the period to 1 decimal place into the bargain! In an attempt to counter the proliferation of unhelpful orbits in the literature van den Bos was driven to write a paper called ‘Is this orbit really necessary!’

Discovery

As early as the 1840’s Sir James South bemoaned the fact that Struve (F.G.W.) had swept the sky clear of new double stars and there was little left for him to do. Twenty or so years later when Burnham began to find many new pairs using a 6-inch telescope even T.W.Webb expressed the view that he could not hope to keep up this rate of discovery. In fact this was just the start of a golden period for visual discovery which lasted in essence until the middle of the last century. After that it is fair to say that minds were concentrated on getting more observations of the existing systems in order to accumulate stellar masses and dynamical parallaxes. Even so the work of Paul Couteau and Paul Muller in France and Wulff Heintz in the USA indicated that there was no shortage of new pairs for those prepared to look for them with suitable apertures. The Hipparcos satellite which operated between 1989 and 1993 found about 15,000 new systems, some of which would have been too difficult for visual observers but some of the pairs can be resolved visually and the widest discoveries have been seen with very small telescopes. Hipparcos, and the associated Tycho mission which looked at other observations made by the satellite to a fainter magnitude but with less accuracy than the main mission, was by no means a complete survey.

In short there are still new double stars to be found either by lunar occultation or by visual examination in a concerted manner of, say, POSS films. As already mentioned, Schmidt survey films or prints can show stars down to 5” separation. In his study of the pairs on POSS prints originally found on astrographic plates by Pourteau, Domenico Gellera noted a number of closer components in these systems. These pairs have not been confirmed so far but at typical magnitudes of 12 to 16 and separations of about 5 arc seconds, these could be recorded with a 10-inch Schmidt-Cassegrain with a CCD camera. (See the photo on page xxx). The power of modern telescopes and CCD cameras is such that even pointing at a random area of sky, one is likely to record pairs which are not catalogued.

Direct visual discovery is another matter. New pairs still turn up and the French observer Jean-Claude Thorel using the 50-cm refractor at Nice has discovered 4 to date but these are by-products of a measurement programme rather than a deliberate attempt to survey for new discoveries. Sky conditions, particularly seeing, would need to be very good so that stars surveyed show sharp round disks and any close companion (within range of the telescope) would be relatively easily visible.It is one thing to measure a known pair whose separation is below the Airy limit but it is quite another to discover one at the same distance.

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Chapter 21
Some active amateur double star observers

Bob Argyle

21.1 Introduction

Although some effort has been expended to try and collect as much information as possible about the current activities of individuals and groups involved in double star observing the following notes should be taken as a guide only. In each case the contact details are given in the Appendix.

21.2 USA

Double star astronomy in the amateur community was first organized on a national scale by Ron Tanguay who founded the magazine called the Double Star Observer. In Spring 2005, and hosted by the Univesrity of Southern Alabama the Journal for Double Star Observers was first issed and since then has been available free of charge on the Alabama website. `http://www.jdso.org`. It is edited by R. Kent Clark and with Brian Mason of the USNO acting in an advisory capacity. Issued four times a year it reflects the work of both international and home grown observers.

The most actie observers in the US are Dave Arnold and James Daley.

21.3 France

France has always been a centre of excellence for double star studies. In the last century observers such as Robert Jonckheere and Paul Muller were very active observers and discoverers. The latter also developed the double-image micrometer. The leading amateur was Paul Baize who was not only a prodigious observer but also computed orbits, many of which remain in the catalogue today. Antoine Labeyrie developed speckle interferometry which has had a profound effect on the observation of very close visual binaries and which has allowed large telescopes to be used to their full resolution capability.

Fig. 21.1 Dr. Paul Couteau (right) with Bob Argyle at Santiago de Compostela in August 1996 (Angela Argyle)

For the present generation, the leading professional figure is undoubtedly Paul Couteau (born 1923) with more than 2700 discoveries to his credit and 25,500 measures. Dr Couteau has spent a great deal of his career at the Observatory of Nice where today double star research still continues.

Under the auspices of the Commission des Etoiles Doubles of the Soci/’et/’e Astronomique de France, a team composed of Guy Morlet, Maurice Salaman and René Gili has for some years now been taking advantage of the capabilities of the CCD imaging technique using the 50 and 76 cm refractors at Nice Observatory.

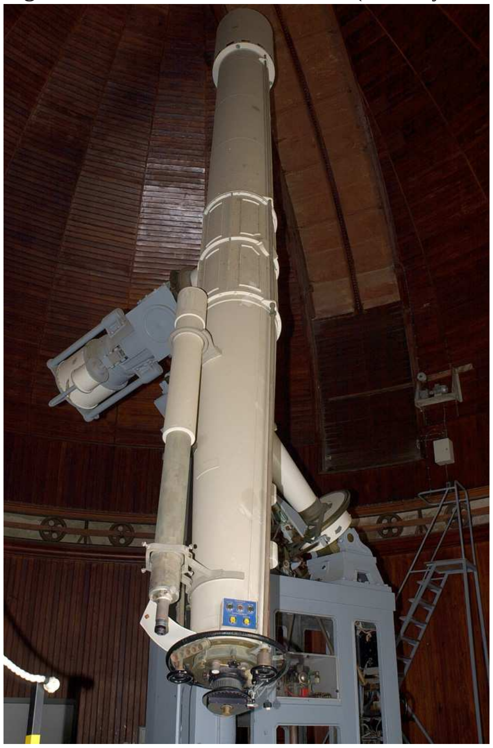
Whilst the 17.89 m focal length of the 76 cm refractor did not require any change, the 7.50 m focal length of the 50 cm refractor has been increased to 15.50 m using a 2x Barlow lens (Clavé). The CCD camera presently in use is a French LE2IM, a Hi-SIS 23 with a Kodak matrix KAF 401E (758 x 512 square pixels of 9μ).

The imaging software is either QMIPS 32 or QMIPS. Short exposures of 1s down to 0.02s are taken. For every pair, 200 images or so are currently saved on the hard disk of a portable computer.

Observations are later reduced after the 10 or 15 best images have been selected and composited (ie shifted and added) using MIPS. The measurement of composite images is achieved using specific software for determining the position angle, angular separation and magnitude differences

From 1997 to 2000, seven observing sessions have been conducted at Nice Observatory and the team measured some 300 different pairs down to $0''.4$ with the 50-cm refractor and to $0''.3$ with the 76 cm refractor, demonstrating that CCD imag-

Fig. 21.2 The 50-cm refractor at Nice (Courtesy R. Gili)



ing technique fits the needs of double star measurement well, giving very reliable results and allowing the best use of observing time.

Jean-Claude Thorel is one of the leading visual observers in France today. His interest in astronomy started during a childhood illness when he was kept in isolation and his father brought him a book on astronomy to pass the time. It was some 15 years later that the interest in astronomy returned and he bought a 60-mm refractor to use at his home in Villepreux, close to Versailles. This was followed by a 20-cm Schmidt-Cassegrain and his early interests included lunar and planetary drawing and deep-sky observation. His first serious work was comet observation, resulting in a published guide on to how to observe and draw them.

He then became involved in work to resolve some inconsistencies in double star catalogues during the construction of the Hipparcos Input Catalogue. This involved two trips to use the 1-metre telescope at Pic du Midi in 1986 and 1987. This expanded into a general programme to measure neglected and problem pairs in the double star catalogues using the 50-cm and 76-cm refractors at Nice. He has recently been working on a programme of checking the double stars discovered by the Tycho mission on the Hipparcos satellite - some 4800 of which are visible from Nice. This had meant travelling from Villepreux to Nice three or four times a year,

Fig. 21.3 The plate at the back of the refractor can be shifted in the focal plane. It supports both the CCD camera and the eyepiece used for visual control of the field (Courtesy R. Gili).

a return trip of 2,000 km but his job now means that he is able to live in Nice and take advantage of the proximity of the telescopes there.

He has made 6,000 micrometric mean measures with the refractors at Nice, including 4 new pairs (JCT1-4) and has also published a biography of Robert Jonckheere amongst other works.

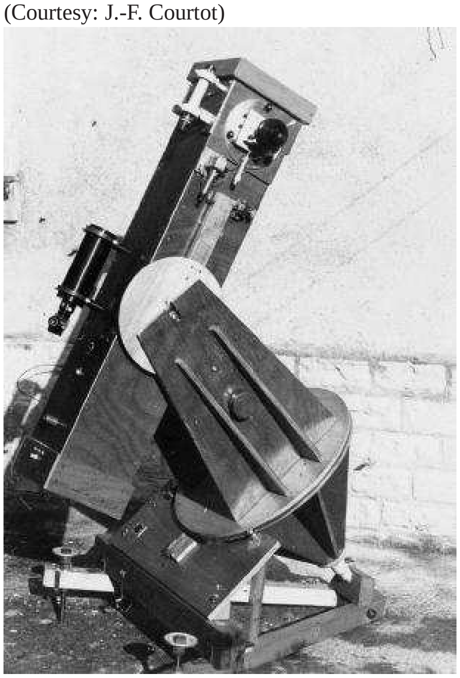
Meanwhile in North-East France, Jean-François Courtot has been engaged in double star research since 1993 but he has been interested in astronomy from youth. He uses a homemade 205 mm Newtonian from Chaumont.

For wide pairs, a chronometric method, the transit method, is often used (3). The angular separation is derived from the time needed by components to successively cross the same thread because of diurnal motion. Each measurement consists of 6 alternate readings ($\pm 180^\circ$) of the position angle and 20 determinations of the transit time. The mean internal error for the position angle is usually $\pm 0^\circ.2$ and $\pm 0''.3$ for the angular separation.

For closer pairs, a filar micrometer has been installed to measure separations occasionally down to 0”.66, the practical diffraction limit under good seeing with the 205-mm telescope. Each measurement consists also of 6 alternate readings of the position angle while 3 double-distance measures of separation are taken. For pairs close enough to be observed at the same glance under magnification x 500 without darting rapidly from one star to the other, the filar micrometer allows the mean internal error to be kept typically within $\pm 0^\circ.1$ and $\pm 0''.03$. This latter limit is the equivalent reading accuracy allowed by the screw constant and the overall focal length.

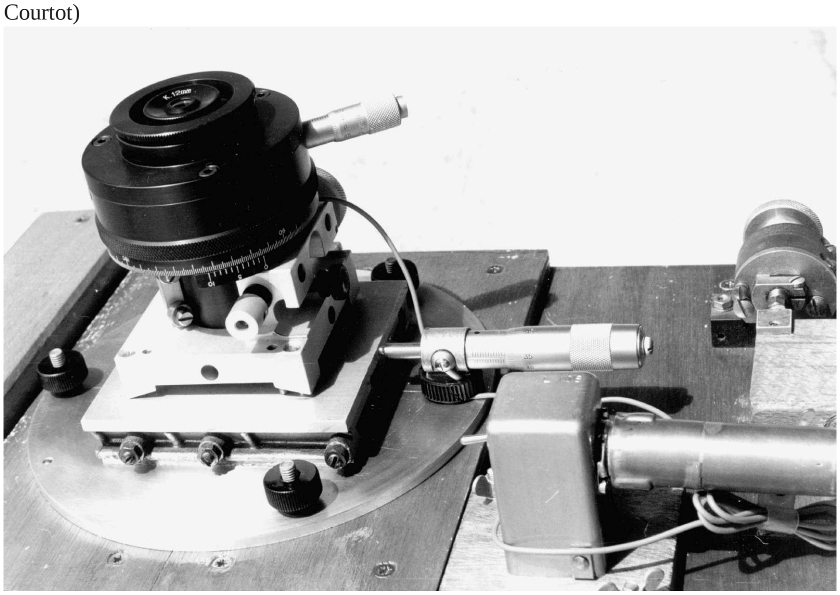
Fig. 21.4 Jean-Claude Thorel in his office at Nice

Fig. 21.5 The 205-mm reflector used by Jean-François Courtot in Chaumont, north-east France (Courtesy: J.-F. Courtot)



To compensate for various seeing conditions and more or less controllable errors, the measurement of a given double is usually repeated on 3 or 4 different evenings. For the closest pairs, bright components ($V < 7.5$) and stable seeing are needed. Wide pairs accommodate to fair conditions and can sometimes be measured down V=10.

Fig. 21.6 The RETEL micrometer attached to the 205-mm reflector of Jean-François Courtot (J.-F. Courtot)



So far, some 3000 measurements of 800 different doubles have been completed, published (1,2,4) and included in the WDS data base, some but a few of these pairs having never been observed before. Aside from observations of orbital and neglected systems, proper motions of optical pairs are checked using historic double star measurements as a start point and new determinations are proposed at times.

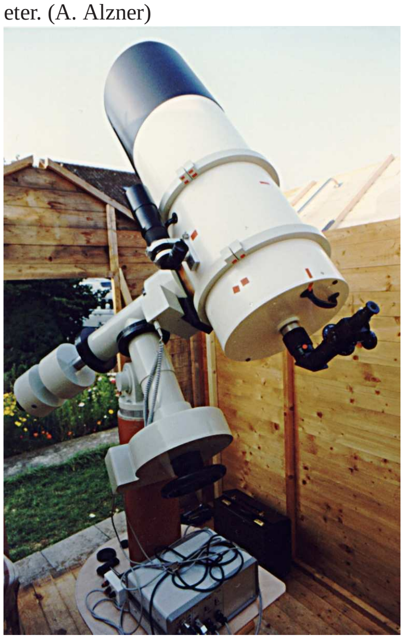
Florent Losse is well-known for his REDUC software which is widely used by amateurs to reduce CCD observations. Since 2002 he has also made more then 2.500 measures of close pairs using a variety of telescopes. Beginning with a webcam on his 8-inch Newtonian in 2002, he added a CCD in 2004 and more recently has been doing speckle interferometry with a CCD attached to his 16-inch Newtonian. (http://www.astrosurf.com/hfosaf/)

Many of the results from French observers appear in the publication *Observations y Travaux*, published by the SAF.

21.4 Germany

Andreas Alzner operates a 32.5-cm Cassegrain and 35-cm Newtonian in an observatory at Hemhofen, just outside Erlangen. The telescopes are equipped with both RETEL and van Slyke filar micrometers and a Meca-Precis double-image micrometer.

Fig. 21.7 Fig 20.8 The 32.5-cm Cassegrain of Andreas Alzner fitted with a Double Image micrometer. (A. Alzner)



Dr. Alzner has also published a number of orbits in Astronomy and Astrophysics and concentrates on close pairs, down to 0.25 arc second, including also some of the first measures of Hipparcos discoveries from the ground. He is the author of Chapters xx and yy here.

Dr. Rainer Anton lives near Kiel. Starting in 2002 he has used of video cameras for double star imaging which gave a pixel size of 0".19 when used in zoom mode on his 20-cm telescope. More recently has been using the technique of lucky imaging which he describes in Chapter xx. In collaboration with other German colleagues such as Karl-Freidrich Bath he has also made some trips to Namibia to use the telescopes at the Internationale Amateur-Sternwarte outstation in the Gamsberg Mountains in Namibia (`http://ias-observatory.org` to make observations of southern double stars. Dr. Anton is a regular contributor to JDSO (http://www,jdso.org)

Jörg Schlimmer has been using Phillips toUcam pro 740k webcam on his 8-incn reflector whose basic 800-mm focal length can be increased to 1500mm and 3000mm by use of Barlow lenses. In the latter case the pixel size is 0”.34. (See JDSO 6, 197, 2010)

21.5 Hungary

The Hungarian Double Star Section, established in 1992, publishes a column in the monthly journal of the Hungarian Astronomical Association, *Meteor*. Since 2010 its leader has been Tams Szklenr. So far 150 amateurs have made 15.000 observations of more than 7500 pairs. Most of these are visual observations. Only the amateur Ernö Berkö of Ludnyhalszi measures the doubles regularly: from 2001 with a CCD camera, and since 2007 with a DSLR camera and a 35.5 cm reflector. He measures mostly the neglected pairs of WDS, but in the meantime ? up until February 2011 ? he has also discovered more than 1100 new pairs, which have been catalogued. Sometimes Tamás Ladányi and Gyrgy Vaskti measure double stars, too, of which 2 have been catalogued under Tamás Ladányi’s name. Since 2002, Ernö Berkö, Tamás Ladányi. and György Vaskti’s articles have been published in the Circulars of the Webb Society Double Star Section, from issue 10 on. These publications contain measurements, as well. Ern? Berk?s measurements of binaries have also appeared in the American *Journal of Double Star Observations* since 2007.

21.6 Spain

The first measurement catalogue entirely produced in Spain by an amateur was that by J. L. Comellas. The first, published in 1973 (Catálogo de Estrellas dobles Visuales 1973.0) contained measurements of 1200 double stars, using several reticle micrometers and a 75-mm aperture Polarex-Unitron refractor. A revision of this catalogue was published in 1978 inside Comellas’s Guia del Firmamento handbook. Twelve years later the same author published a second catalogue (Catálogo de Estrellas Dobles Visuales 1980.0) that included 5114 doubles within reach of his new 102 mm aperture Polarex-Unitron refractor installed in his observatory with a 2 metre dome, of which he personally measured over 3500. These two works were published by Agrupaci/’on Astronómica de Sabadell (AAS) and Editorial Sirius respectively.

Since 1985 other observers have maintained the continuity of Comellas’ work. From 1976, T. Tobal regularly collaborated with him, and in the mid-1980s he built a small observatory equipped with a 102-mm Polarex-unitron refractor and a reticle and filar micrometers constructed by J. A. Soldevilla, allowing him to start a systematic revision and updating the 1980.0 Comellas’s Catalogue. In 1991,in conjunction with other colleagues, T. Tobal coordinated the measurements sent by individual ob-

Fig. 21.8 The Spanish double star observer, José-Luis Comellas (T. Tobal)

servers and began to publish a periodic circular (RHO: Circular de Estrellas Dobles Visuales) for internal use, in order to coordinate the work and to publicise the results. J.Planas developed the MAIA software, meaning to prepare the massive compendium of Spanish measures from 1970 to USNO/WDS standards. J. Cairol, I. Galn and A. Sánchez typed thousand of data from paper to computer database. Subsequent acquisition of new precision micrometers, double image Lyot-Camichel-like, and CCD devices came off, and between 1992 and 2000 more than 5000 new observations and measurements were collected, provided by amateurs throughout Spain.

In 1991 the Garraf Astronomical Observatory (OAG) was founded and in the original site (1992-1998) a 3.5-m diameter dome with a 260-mm F/6 aperture Newtonian was installed. Then a new observatory was constructed using public and private investment. Located 30 Km. South of Barcelona, inside the Garraf Natural Park was opened in November 2001. It has a new 3.5-m dome and a 30-cm Newtonian-Cassegrain f/3.5 and f/13 telescope fitted with a CCD camera and a Lyot double-image micrometer and others devices for double stars working.

In 2003 a final compendium of about 10.000 measurements made between 1970 and 2003 was coordinated by the staff of OAG. This work was presented at the First International Meeting of Double Star Observers, the first meeting between Spanish and French observers that took place in Castelldefels (Barcelona, Spain) in 2000. It was organized jointly by the Agrupación Astronómica de Castelldefels (AAC), Observatori Astronómic del Garraf (OAG) and the Commission des Etoiles Doubles (SAF). The OAG General Catalogue of 10,000 measurements 1970-2003 (coordinated by T. Tobal & J. Planas) is only available in electronic format at the USNO / WDS and OAG web site.

Since 2004 the interest in double stars in Spain has grown significantly appearing new observers and teams. R. Benavides, J. L. González and E. R. Masa, founded in

Fig. 21.9 The observatory in the Garraf National Park, near Barcelona.

2009 the electronic magazine El Observador de Estrellas Dobles, a specialized magazine in Spanish language available at `http://elobservadordeestrellasdobles.wordpress.com/`.

Other active observers are F. Rica , coordinator of Double Star Section of LIADA international group (http://sites.google.com/site/doblesliada/) , I. Novalbos and J. A. Santos in charge of electronic measures (http://oanlbcn.blogspot.com/) and R. Hernández, J. Torell with and N. Miret managing the OAG orbit calculation team. Another important observatory with a 40-cm telescope, full equipped with CCD and spectroscopic devices was funded by J.Genebriera in La Palma (Canary Islands) (www.astropalma.com), who is an active observer in several OAG and professional projects.

New programs began to take shape after 2005, aimed at reviewing neglected double stars in WDS catalogue and detecting anonymous pairs. The OAG Supplements (2005-2008) include more than 4,000 new measures and more than 500 new pairs.

In mid-2008 the OAG team started a systematic exploration of the Equatorial Zone (Dec +20° to -20°) on digitized images from professional surveys designed to find anonymous common proper motion systems with ¿50mas/year (OAG Common Proper Motion Wide Pairs Survey). Nowadays 11 teams throughout Spain in collaboration with several professional teams (J. A. Caballero, E. Montes, E. Solano and D. Valls) are working on it. In late 2010, more than 600 new pairs not listed before were included in the USNO / WDS catalogue, emphasizing the contribution of A. Bernal (Observatorio Fabra, Barcelona). This project is coordinated by X. Miret, T. Tobal, and I. Novalbos of OAG and C. Schnabel of the AAS. Project details and complete list of participating observers in this and other historical projects, can be seen at www.oagarraf.net.

This new period had its culmination in the Second International Meeting of Double Star Observers that took place in (AFEGIR nota 1) Sabadell (Barcelona, Spain), October 2010, witch joined professional and amateur observers, from Australia, France, UK, USA and Spain.). The full presentations and articles are available at (http://ad.usno.navy.mil/wds/dsl.html.

Fig. 21.10 The joint meeting between European double star observers held in October 2010

21.7 South Africa

The Double Star Section of the Astronomical Society of Southern Africa is led by Chris de Villiers. He has recently successfully experimented with speckle imaging using the 18-inch refractor at the South African Astronomical Observatory in Cape Town. More details can be obtained from his web site which is given in the Appendix.

21.8 United Kingdom

The Webb Society Double Star Section started in 1968 and Bob Argyle became Director in 1970. It was not until the end of the decade that some preliminary attempts to measure double stars using grating micrometers and home-made filar micrometers were made. By the end of the 1980's the availability of commercially made filar micrometers allowed members to make micrometric measures. At the time of writing the results have been published in nineteen Double Star Section Circulars most of which have now been incorporated in the Observations Catalogue of the United States Naval Observatory. Using the 8-inch refractor at the Cambridge Observatories, Bob Argyle is carrying out a programme of visual measurement (see Chapter 21). The programme consists of a number of long-period binaries plus observations of some wider, fainter pairs. Including two periods of observation with the 26.5-inch refractor at Johannesburg some 7,350 micrometer measures have been made since 1990.

Tom Teague, using an 8.5-inch reflector near Chester, has developed a new and more efficient way of using a Celestron Micro Guide eyepiece and he describes the use of this instrument in Chapter xx.

John Greaves has concentrated on using on-line astrometry from recent catalogues such as the Sloan Digital Survey to identify wide common proper motion pairs. To date, the WDS catalogue contains 1247 systems discovered this way.

The work done by the Webb Society can be found at http://www...

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Chapter 22
An observing session

Bob Argyle

22.1 The telescope

In this chapter I describe a typical observing session with the 8-inch (20-cm) Thorrowgood refractor at the Institute of Astronomy in Cambridge. The telescope belongs to the Royal Astronomical Society but is on permanent loan to the Cambridge University Astronomical Society and has been on its present site since 1930 (Fig. 21.1).

It was built by Cooke in 1864 for the Reverend W. R. Dawes who did not have much opportunity to use it. It passed through the hands of W. H. Maw, a founder member of the British Astronomical Association and an active double star observer, before ending up in the possession of W. J. Thorrowgood, who, in turn, bequeathed it to the RAS.

Fig 21.1 The 8-inch Thorrowgood dome

The telescope is on a German mount and is driven in RA by a small synchronous electric motor. The focal length of the object glass is 114 inches giving the telescope a focal ratio of just over f/14 and a scale at prime focus of 71.2 arc seconds per mm. There are slow motion controls in both RA and Dec each of which run on tangent arms and consequently have to be reset every night or two. The telescope can be used either side of the pier but my own practice is to work on the east side of the pier since clamping the telescope this side is much easier and speeds up observing. In addition, the slow motion controls are to the right of the eyepiece and more comfortable to work with.

22.2 The micrometer

I use a RETEL micrometer is to make the measures (Fig 21.2). There are three wires in the field of view of the eyepiece. Two are fixed and perpendicular to each other; the third moves in two directions and used in conjunction with the fixed wire parallel to it measures the separations whilst the other wire is used for position angles. The movable wire is controlled by an engineering micrometer screw which has a range of about 11.5 mm and which can be read to 1 micron using the fitted vernier. The wires have a diameter of 12 microns, which translates to 0”.85 in the focal plane. As the telescope will resolve pairs about 0”.55 apart this is plainly unsatisfactory. This can be easily overcome by means of a Barlow lens. In this case I employ a x3 Barlow which triples the effective focal length and reduces the apparent size of the wires in the eyepiece to about 0.3 arc seconds. In conjunction with the 18 mm Kellner eyepiece supplied with the micrometer this gives a magnification of about x450 and this is used for all measures.

The field is illuminated by a single red LED which can lead to parallax problems if the illumination is set too high. A way out of this is to locate an LED in the telescope dewcap thus illuminating the field more evenly. On bright stars it is best to turn the ilumination down or even off to set the wires since they can be seen in shadow against the star disks. Using the manufacturer’s illumination I can measure wider pairs down to about V=10 and for faint, close pairs then STF1280 (mags 8.9 and 9.1 at 1.2 arc seconds) represents the limit for the 8-inch refractor.

Fig. 21.2 The RETEL micrometer and Barlow lens mounted on the 8-inch Thorrowgood refractor

Although it is clearly better to have a micrometer residing permanently on the telescope, in my own case this is not possible since the telescope is often used for other observations including solar projection. Hence it must be fitted and removed for each observing session. I therefore have to check the instrumental position angle of standard pairs at the beginning and end of the night. I also measure the separations of the same pairs to give a determination of the scale of the micrometer by taking a mean of the two determinations which usually agree to within 1

Whilst the micrometer is being fitted to the telescope, the dome is opened to allow the inside air to come to the same temperature as the air outside. As the dome is fairly small this does not take very long. A note is made of the dome temperature at the beginning and end in case refraction corrections need to be made and to check whether any scale variation in the micrometer with temperature is discernable. In practice I don’t do this. For pairs ¡ 30 ” in separation the correction is very small.

22.3 Other accessories

For observing I take the following items: a notebook in which the raw micrometer readings are written. These are transcribed to another volume later and the reductions made at home. A star atlas with the target stars marked. I have found that using Norton’s Star Atlas and simple star-hopping is adequate in the vast majority of cases. The telescope is fitted with setting circles but there is no sidereal clock in the dome and the circles are not that easy to read in subdued light. When the pair is in a rich starfield it is occasionally necessary to take a more detailed map of the stars nearby in order to locate the pair in question. A torch with a piece of red plastic over the window allows the micrometer readings to be clearly seen as well as affording enough light to write down settings. Finally a list contains the stars to be measured along with the number of nights which each one requires and the number left to do.

22.4 Measurement plan

My policy is to measure the most interesting binaries on at least 5 nights each year. Some such as Castor (alpha Gem) tend to get more than this because the star is so bright it can be seen in twilight and observing can start earlier when the seeing can be rather good. The standard pairs used also tend to be rather bright for the same reason. Relatively close pairs (at around 1 arc second) which are measured occasionally because they are slow-moving get 4 nights and any other pairs (usually wide) get 3 nights. As for the number of settings made on each individual star this tends to depend on the difficulty of the pair. In the summer of 1999, for instance, the fine binary zeta Her which consists of stars of mag 2.9 and 5.8 was separated by just under an arc second. This meant that measuring the companion depended very much on sufficiently good seeing but, even so, setting the position angle wire resulted in values which scattered by as much as 15 or 20 degrees. In this case, I make up to 8 settings in position angle. For wider pairs, where the separation is perhaps 20 or 30 arc seconds, the agreement between individual angle settings is usually better than 1 degree and 4 measures are deemed sufficient.

It is very useful to mark up the target stars on the star atlas because another time-consuming activity is moving the dome by hand. By concentrating on a number of pairs in the same region of sky not only can these be observed more quickly but a comfortable observing position need not be disturbed too often. Having said that, trying to see stars near the zenith with a long-focus refractor requires the ability of a contortionist and I tend to avoid stars which are too high in the sky. There is no doubt that comfort is a significant advantage in securing better measures.

The pairs to be measured will depend on several factors, the prime one being the seeing. If the seeing turns out to be particularly good then I tend to concentrate on the closest pairs. If seeing is poor then wider pairs can be tried. It is very rare in Cambridge that stars of 1 arc second separation cannot be measured so it is clear that the city environment is not necessarily a bad one even though the sky is usually rather bright. Another factor may be the number of observations left for a particular pair. It is better although not necessary to try and get sufficient measures for a mean during the same season. For wider pairs which are slow moving it may be 3 or 4 years before I get sufficient measures for a mean.

A red torch is used througout. For examining the star atlas for the location of the next pair, looking the verniers on the micrometer and writing down the settings in the observing sheet. A simple hand-held torch with a button to allow the light to be flashed on and off is most efficient. Rechargeable batteries soon recoup the initial outlay.

22.5 Measurement

In measuring each pair the position angle is always done first and although formally the wire should be reset at the end of this procedure to the mean value in practice this is not done since the individual values tend to agree closely enough for this purpose. Two to four settings are made and the individual angles remembered before writing them down. For wide pairs these will usally agree to within one degree and it is then only necessary to remember the decimal part. It is recommended that the quadrant in which the fainter star lies is noted. With equatorial telescopes the approximate directions of the cardinal points are usually fairly obvious so it is a simplematter to record whether the companion star is in the first quadrant (i.e. with a PA between 0 and 90°) or another quadrant. This is because the recorded PA from the micrometer is ambiguous by 180 degrees depending on where the micrometer barrel is pointing. I happen to be right-handed so the micrometer barrel is usually in the first or second quadrant.

For separation, the technique used depends on the distance between the stars. For close pairs (¡ 15”) the double distance method is used and the two values of the screw are written down at the end of the procedure. For wider pairs it is too time-consuming to do this so four settings are made with the movable wire on one side of the fixed wire then another four settings made with the movable wire on the opposite of the fixed wire. This requires the use of the telescope slow motions and this is where a box screw would be useful. On the older brass micrometers this was an arrangement which allowed all the wires to be moved across the field of view whilst retaining their absolute position with respect to one another. With the RETEL micrometer the separation readings are in mm on the micrometer screw but each revolution of the screw is graduated in 50 divisions so care must be taken to note whether the reading is between x and x+0.5mm or x+0.5 and x+1.0 mm where x is the reading in whole millimetres on the barrel. In most cases, however, the error will stand out easily and be corrected when reducing the data.

As mentioned above for the Thorrowgood it is necessary to remove the micrometer and Barlow assembly at the end of each session and so one of the first pairs to be measured is a calibration pair. A list of bright pairs with separations from 14 to 100 arc seconds around the sky is used (and is given in Chapter 15). The relative position angles and separations are known to about $0^\circ.1$ and about $0''.05$ - sufficiently small to be negligible compared to measurement or personal errors. The same pair, if possible is also measured at the end of the night. If it is possible to leave a micrometer in place on the telescope then this is the best option - even so, the zero of position angle should be checked at least once per night.

22.6 Reducing observations

The observed micrometer settings are taken home where they are copied with a little more neatness into an observing book (Fig. 3). The original recordings are kept in case of a query or transcription error. It is at this point that the mean settings are calculated and the position angles and separations worked out.

Fig 21.3 An extract from the author's observing book. The two central columns record the settings of the movable wire in millimetres corresponding to the double distance method. The right hand column gives the observed position angle on the micrometer barrel. This is converted to the true PA and separation by using the reference pair δ Boo. The final observed PA and separation are given along with the epoch of observation in decimals of a year. Note the correction to the mean PA of STF 1932. It is easy to misread the micrometer dials in the dome!

The two observations of the calibrations are done first. This gives a mean value for the observed position angle at the beginning and end of the session. This usually agrees to better than 1 degree. The difference between the instrumental value and the value from the calibration list is the correction to be applied to all the other mean position angles. Similarly a mean screw value is obtained from the calibrations and applied to the remaining observations. The final touch is to convert the calendar date to a decimal of a year. This can be done via a lookup table which can be found in the Explanatory Supplement to the Astronomical Ephemeris or the program JD&EPOCH in the 'soft' folder on the accompanying CD-ROM can be used. High resolution work such as speckle interferometry on rapid visual binaries is usually in time using the date to 4 decimal places but for visual work with small telescopes, 3 places of decimals is more than adequate.

Chapter 23
Some useful formulae

Michael Greaney

23.1 Introduction

The observations brought inside after a night at the telescope represent just raw data. A number of steps must be taken to reduce this data to meaningful observations. These steps will include expressing the time of each observation as a standard epoch and reducing the observed magnitudes of the individual components. Consideration will also have to be given to any effects that atmospheric refraction might have on the relative positions of the components. If the observations are to be reduced to some standard epoch then corrections must be made for the effects of precession and proper motion on the position angle. It might be interesting also to compare the observed position angle and separation with the expected values. This will entail calculating them from the orbital elements of the system.

The calculations involved can be carried out quite readily with some simple computer programs. The programs given here are written in QBasic, which is bundled with the Microsoft Windows 95, 98 and Millenium edition operating systems. However, QBasic is not installed as part of the Windows installation process and has to be installed manually. The process is really quite simple. Go to the TOOLS directory on the Windows CD and then to the OLDMSDOS subdirectory where the two QBasic files will be found. (One is then EXE file, the other, which has an icon of a book, is the help file.) Highlight the files and then drag them over to the WINDOWS directory on the computer's hard drive. From there double click on the EXE file to launch QBasic (although it might be more convenient to install a shortcut on the desktop or start menu and launch it from there).

23.2 Dating observations

The date of a double star observation should be expressed as the year in fractional form, usually to three decimal places. This is known as the epoch of the observation.

There are two forms of epoch that have been used in dating double star observations: the Besselian epoch and the Julian epoch.

The Besselian epoch is base on the length of the Besselian year of approximately 365.2422 days and is given by
Besselian epoch = B1900+(JD-2415020.31352)/365.242198781

where the prefix B indicates that it is a Besselian epoch, JD is the Julian date and the constant 2415020.31352 is the Julian date of the standard epoch B1900, i.e. 1900 January 0 (= 1899 December 31).

The Julian epoch was introduced with the new astronomical constants in 1984. It is based on the length of the Julian year of exactly 365.25 days and is given by
Julian epoch = J2000+(JD-2451545)/365.25

where the prefix J indicates that the epoch is a Julian epoch and the constant 2451545 is the Julian date of the standard epoch J2000, i.e. 2000 January 1 at 12 hours Universal Time (UT).

The prefixes B and J are used only where context or accuracy make them necessary.

Dating an observation to three decimal places means effectively dating it to an accuracy of nearly nine hours. This means that a single Julian epoch value could serve for about four or five hours of observing time. So it is possible that a single epoch value could serve for a whole observing session.

The program JD_EPOCH.BAS returns the Julian epoch for a given date and time. The Julian date is calculated in the course of calculating the Julian epoch and as it is widely used in astronomy, for dating variable star observations for example, it is also returned.

The value of the constant TZ near the beginning of the program needs to be set to that of the local time zone. This enables the time to be entered as the local time; otherwise the program assumes the time at Greenwich. Hence, for the North American Eastern Standard Time TZ = -5, whereas for New Zealand Standard Time TZ = 12.

Let us date some hypothetical observations made in New Delhi, India between 7pm to 11pm (local time) on Christmas Eve 2001. TZ in this case would be 5.5. Now the mid-point of the observing session would be 9pm, i.e. 21 hours. The data would be entered into the programme as

Enter the date (yr,mth,day)? 2001,12,24

Enter the time (hr,min,sec)? 21,,

The results would be

Julian date = 2452268.1458

Julian epoch = 2001.980

Enter the hour followed by two commas, rather than entering zero minutes and zero seconds when entering only the hour for the time.

23.3 Position Angle and Separation

Measurements made of double stars are used to determine the orbital elements of the binary system. These can be used subsequently to calculate the visual aspect, i.e. the position angle and separation, of the binary for a given date. The program PA_SEP.BAS carries out such calculations.

The program asks for the orbital elements of the system first. In this program they are in an order that corresponds with the US Naval Observatory's Fifth Catalog of Orbits of Binary Stars, which can be found on the Internet (see Appendix C). There are other tables of orbital elements available, but these might not list the elements in the same order. However, the input statements for the orbital elements in the computer program can be arranged in any order, just be aware that the input statements for the period and for the eccentricity are contained in do-loops so the whole loop will have to be moved if either of these input statements is to be moved.

The first step in calculating the position angle and separation is to find the mean anomaly. This is the proportion of the period that has lapsed since the last passage of periastron and is expressed in angular measure. So if one-third of the period had lapsed then the mean anomaly would be 120°.

Once the mean anomaly has been found the eccentric anomaly has to be found. This is carried out by evaluating Kepler's equation M = E - e sin E. It is an apparently simple equation, but it is an example of what is called a transcendental equation and can not be solved explicitly for E. The solution is found by assuming an initial value for E (which is never greater, or less, than M than an amount equal to e, when M and E are expressed in radians) and then evaluating the equation to see if it gives the right value of M. If it does not, at least to a predetermined level of accuracy, then the value of E is amended and the equation re-evaluated. This process of iteration continues until the required level of accuracy is achieved. Finding methods of evaluating Kepler's equation has been one of the most intriguing problems in mathematical astronomy since Kepler published it. Even the best initial value for E has been the subject of much investigation.

The importance of finding the eccentric anomaly is that enables the true anomaly (v) to be found. Once this has been found we can define u as the sum of the true anomaly and the argument of periastron (ω), i.e. u = v + ω.

We can then define

x = cos u

y = sin u cos i

and hence obtain expressions for the position angle (θ) and separation (ρ)

$$tan(\theta - \Omega) = \frac{y}{x}$$

where Ω is the position angle of the ascending node

$$\rho = r\sqrt{(x^2 + y^2)}$$

where r is the magnitude of the radius vector

This expression for the separation is not the standard one, which is

$$\rho = \frac{rcos(\nu+\omega)}{cos(\theta-\Omega)} = \frac{rx}{cos(\theta-\Omega)}$$

The difficulty with the standard expression is that the denominator will equal zero whenever $\theta - \Omega$ equals 90°and 270°. Recasting the equation in the alternative form obviates any difficulty that would arise if this situation should ever be met in practise. It has to considered, though, whether the expression contained in the square root radical will ever be negative as that would cause problems, but as both x and y are squared and then added together, that situation will never occur. The alternative form, then, provides the computer program with greater integrity. Furthermore, as x and y are used to calculate both the position angle and the separation there is less evaluation of trigonometric terms. This makes the alternative form computationally more efficient.

The expression for the position angle suffers from the same defect, namely that it becomes undefined whenever x equals zero. However, in such instances the matter can be resolved by the sign of the numerator, y: if it is positive then $\theta - \Omega$ equals 90°while if negative $\theta - \Omega$ equals 270°. The same line of reasoning can not be applied to the standard expression for the separation, because it turns out that whenever the denominator is zero the numerator is also zero.

As an example, calculate the visual aspect of our closest double star Alpha Centauri (WDS 14396-6050) for the middle of the year 2002; hence the date of observation will be 2002.5. The input values will are given below. The brackets contain the designations used on the USNO's web page. Note that Omega, with a capital O, represents Ω while omega, with a lower case o, represents ω. The Greek letter designations are normally found in other tables of orbital elements.

Period	79.90	(P)
Semi-major axis	17.59	(a)
Orbital inclination	79.23	(i)
Position angle of the ascending node	204.82	(Omega)
Epoch of periastron	1955.59	(T)
Orbital eccentricity	0.519	(e)
Argument of periastron	231.8	(omega)
Date of Observation	2002.5	

These values give

Position angle = 225.4 degrees.

Separation = 12.41 seconds of arc

The program can be tested against further examples taken from the USNO's web page. Click on the E in the right most column of the table of orbital elements to see the ephemeris of the star. Clicking on the P next to the E gives a diagram of the orbit.

The whole table of ephemerides of double stars can be found on the USNO web page (see Appendix C) The E on the table of orbital elements links to this page.

23.4 Precessing the Position Angle

Now it may turn out that the calculated position angle of the double star might not correspond with what is observed through a telescope. One reason for this that the orbital elements might not have been determined to a sufficient degree of accuracy. Continuing to measure such doubles will help to amend the insufficiency. Another reason for the discrepancy is that the position angle will have changed with time due to precession. This particular difficulty can be resolved more immediately.

The position angle of the ascending node (Ω) refers to a particular point in the sky, namely the North Celestial Pole. However, the position of the pole moves in time due to the effects of precession and the value of the position angle of the ascending node changes with time as a consequence. The position angle of the ascending node, therefore, has to be reduced to the date of observation to give an accurate value for the position angle. The program PA_REDUC.BAS carries out this reduction. Unfortunately few tables of orbital elements give the epoch of the ascending node, so it might not always be possible to carry out the reduction.

When the epoch of the position angle of the ascending node is given there are two ways to carry out the reduction. First calculate the position angle and separation and then reduce the position angle to the date of observation, or first reduce the position angle of the ascending node to the date of observation and then calculate the position angle and separation. The result is the same either way

The position angle is further affected by the star's proper motion, as the star itself will have moved with respect to the pole. The program also includes a correction for proper motion.

The effects of precession and proper motion on the position angle are greatest for stars of high declinations and large proper motions. It is possible, however, for these two effects to be of opposite signs and consequently diminish the change in the position angle.

Taking Alpha Centauri as an example again, calculate the change in the position angle over the fifty-year period 2000 to 2050. The position angle for 2000 is 222°.3. The position of Alpha Centauri for the epoch 2000 is

Right Ascension 14h 39m 35.885s

Declination -60°50′07″.44

Centennial proper motion in RA -49^s.826

Then we have

Initial position angle 222°.3

Date of initial p.a. 2000

Date of final p.a. 2050

Entering these values into the program gives

Position angle referred to 2050 = 222°.0.

So there is a change of -0.3 degrees over the fifty-year period due simply to procession and proper motion. (Note: this is note the position angle for the year 2050, but the position angle for the year 2000 referred to the pole of the year 2050.)

23.5 Differential Atmospheric Refraction

A further correction to both the position angle and the separation must be made, this time for the effects of atmospheric refraction. The correction should be made in reducing observations as well as when comparing observed with calculated values. The effects are negligible for small separations, as both components are subject to the same degree of refraction, and for stars of small zenith distance, where there is little displacement of star positions due to refraction.

The program DIFF_REF.BAS is derived from the Fortran 77 program developed by RW Argyle. The details of the latitude (Latd), longitude (Longd) and time zone (TZ) near the top of the program should be amended to those of the observing site. If the observations are being carried out at the one site then these values become program constants and only need to be changed if the observing site is changed.

The date and time, the air temperature and pressure, the equatorial coordinates of the star and the position angle and separation are required to calculate the corrections to the position angle and separation. Once these have been entered the program begins by converting the time of day and the right ascension of the star into hours, and the declination into radians.

The first thing to be calculated is the number of days since the standard epoch J2000, i.e. 2000 January 1 at 12 hours UT. A short detour is then carried out to calculate the Julian epoch. The local sidereal time is then found in order to be able to calculate the hour angle of the star, which in turn is used to determine the zenith distance of the star. The greater the zenith distance the greater the effects of atmospheric refraction on the star.

The program then converts the air pressure to millimetres of Mercury and then calculates the normal refraction.

The parallactic angle, which is next calculated, is the angle subtended at the star between the zenith and the pole.

After the zenith distance has been found the program goes on to calculate the corrections to the position angle and separation using Chauvenet's equations. These equations hold only for zenith distances less then 75°.

The program returns the value of the zenith distance along with the corrected values of the position angle and the separation. It also gives the Julian epoch, which obviates the need to run the dating program separately.

The use of the program is best illustrated by considering the effect of atmospheric refraction on a star such as theta Tauri. The position angle of the star is 347°.2 and the separation is 337″.44. Although these are the correct values we will assume that they are the observed values to determine to what degree refraction would affect them. Let us assume that the observation was made from Auckland, New Zealand, on 2001 February 28 at 10pm local time.

We need to know the atmospheric temperature and pressure, along with the position of the star to correct for the effects of refraction on the star. The position of the observer is also required; hence the following changes need to be made near the top of the program: -

CONST Latd = -36.9 'Latitude in degrees.

CONST Longd = 174.8 ’Longitude in degrees.
CONST TZ = 12 ’Local time zone.

For the atmospheric temperature and pressure we will take the values 5°C and 1010mb respectively. The input then becomes

RA of star : hrs,min,sec? 4,28,43.8
Declination: deg,min,sec? 15,52,24
Date: year,month,day ? 2001,2,28
Time: hour,minute,sec ? 22,,
Air temperature: deg C ? 5
Air pressure : mbars ? 1010
Position angle: degrees? 347.2
Separation: arcseconds ? 337.45

The results, then, are

Zenith distance (deg) = 74.517
Corrected values:-
Position angle (deg) = 347.3
Separation (arcsec) = 338.47
Julian epoch = 2001.161

The change in the position angle in this instance is only -0.1 degrees, but the change in the separation is +1″.02. However, if the position angle were 207°.2 there would still have been a change of -0°.1 in the position angle, but only +0″.23 in the separation. This is because the companion would have been higher than the primary and therefore subject to less refraction.

23.6 Estimating Double Star Magnitudes

It is useful to provide estimates of the magnitudes of the components as well as the position angle and separation when measuring double stars. The magnitudes should be estimated to a tenth of a magnitude. A method for estimating the magnitudes is described in the Webb Society Deep-Sky Observer’s Handbook, Volume 1, Double Stars (Second edition), page 24.

The method is as follows: estimate the difference in magnitude between the two components, then with a low power eyepiece, so that the double star appears as a single star, estimate the magnitude of the apparently single star. This will give the combined magnitude of the pair. The combined magnitude can be estimated by comparing the star with two other stars of known magnitudes in the field of view, in very much the same way that variable star observers make visual estimates of star magnitudes. (Such a method is described in The Webb Society Deep-Sky Observer’s Handbook, Volume 8, Variable Stars, Chapter 3)

The equatorial double 70 Ophiuchi appears as a single star of magnitude 3.8. When resolved through a telescope the components are found to have a magnitude difference of 1.8. The magnitudes of the individual components can be found with the program INDV_MAG.BAS.

Combined magnitude 3.8
Magnitude difference 1.8
Magnitude of A 4.0
Magnitude of B 5.8

Providing magnitude estimates enables the stars to be monitored for any variation in brightness. Eta Geminorum and Alpha Herculis, for example, are visual binaries which each has a variable component.

23.7 Triple Stars

There might be occasions when a triple stars are observed. Unfortunately the components are not always spaced sufficiently to measure from a single position. It is not always possible to measure the position of B with respect to A and then rotate the micrometer around and measure the position of C with respect to A. This is because multiple star systems tend to preserve their binary nature. If there are three stars then two of them form a binary while the third component usually orbits the other two as though they were a single star. Likewise, if there were a forth component it would normally be paired with the third component making a binary system where each component was itself a binary.

Measuring a triple star, then, usually entails measure B with respect to A and then measuring C with respect to the AB pair, or more specifically, with respect to the centre of AB. The observation is made this way because when sufficient magnification is used to separate A and B the field of view is usually too small to include C and conversely when the field of view contains C, A and B are usually too close to be separated.

The program TRIPLE.BAS takes as its input values the measurements of B with respect to A and of C with respect to the mid-point of AB. The values of C with respect to A and with respect to B are returned. The calculations involve nothing more than some simple plane geometry.

Measurements of Zeta Cancri for 2001 are
AB $\theta = 78^\circ.3$ and $\rho = 0''.86$ (2001.205, 8 nights)
1/2AB-C $\theta = 72^\circ.9$ and $\rho = 5''.79$ (2001.250, 7 nights)
Hence the program input values will be
Enter the measurements of A->B
Position Angle? 78.3
Separation ? .86
Enter the measurements of 1/2AB->C
Position Angle? 72.9
Separation ? 5.79
Which return
Values for A->C
Position Angle = 73.3 degrees
Separation = 6.22 arcsec

Values for B- $>$C
Position Angle = 72.5 degrees
Separation = 5.36 arcsec

The position angles, in this case, are all close to the same value, which suggests that the three components lie close to a straight line.

The character 1/2, in 1/2AB, can be obtained by holding down the Alt key while typing the number 171.

23.8 Observing Double Stars with an Altazimuth Mounted Telescope

The application of computer technology to telescope drives has enabled sidereal tracking to be automated on altazimuth mounted telescopes. Altazimuth mounted telescopes, however, turn about an axis through the zenith instead of an axis through the pole, as do equatorially mounted telescopes. This means that the fixed pointed on the celestial sphere for such telescopes is the zenith, instead of the pole. As a consequence of this stars in the field of the eyepiece rotate around the centre of the field as the telescope follows the stars across the sky. In the case of a double star this will cause the companion to circle the primary star in the course of the night.

An example of this field rotation, as it is called, is the belt of Orion. In northern latitudes, the three stars that form the belt stand vertically when the constellation is rising, but lie along the horizon when it is setting. In the southern hemisphere the orientation is reversed: lying when rising, standing when setting.

The Parallactic Angle. In order to understand the problem we need to know something about the astronomical triangle. The astronomical triangle is formed by three points on the celestial sphere: the north celestial pole, the zenith and the star being observed. The angle that is of particular interest to us here is the angle subtended at the star between the pole and the zenith, i.e. the angle pole-star-zenith. This angle is known as the parallactic angle and is usually designated by the letter q. The parallactic angle increases as the hour angle increases. When a star is on the meridian θ = 180° if it is on the equatorial side of the zenith, but θ = 0° if it is on the polar side. The reverse is the case for an observer in the southern hemisphere.

The parallactic angle of a star changes in the course of the night, due to its diurnal motion. Its value at any time, i.e. for any hour angle of the star, can be found from

$$tan\ q = \frac{sin\ H}{(tan\ \phi\ cos\ \delta - sin\ \delta\ cosH)}$$

where q is the parallactic angle, H is the hour angle of the star, δ is the declination of the star and ϕ is the latitude of the observing site.

23.8.1 The Position Angle

. As the zenith is the fixed point on the celestial sphere for an altazimuth mounted telescope, position angles measurements made with such a telescope would be referred to the zenith. Let us call position angle measurements made with respect to the zenith, then, the zenithal position angle to distinguish it from the position angle made with respect to the pole.

The direction of the zenith in the field of view can be determined by the same method that would be used to determine the direction of the pole with an equatorially mounted telescope, i.e. a star near the celestial equator is allowed to drift across the field of view, except in this case it must be also close to the meridian.

The position angle can be found by measuring it in the usual way, except, of course, that it is being measured with respect to the zenith. All that needs to be done in addition is to note the time of the observation, so that the parallactic angle can be determined. The parallactic angle is then subtracted from the zenithal position angle to obtain the position angle with respect to the North Pole, i.e.

$$\theta = \theta_z - q$$

where θ is the position angle θ_z is the zenithal position angle and q is the parallactic angle.

23.8.2 Field Rotation

The continual changing of the parallactic angle is known as field rotation and it is the main objection to measuring double stars with altazimuth mounted telescopes. The objection lies not so much in the fact that the orientation of the field is continually changing, but in the rate at which it is changing. The rate of field rotation, therefore, needs to be evaluated to determine the feasibility of being able to measuring the position angle accurately

The rate at which the parallactic angle is changing, i.e. the instantaneous rate of field rotation, can be found by differentiating the above equation for the parallactic angle. Hence,

$$\begin{aligned} \frac{dq}{dH} &= \frac{15cos^2q(tan\phi\ cos\delta\ cosH - sin\delta)}{(tan\phi\ cos\delta - sin\delta\ cosH)} \\ &= \frac{15(tan\phi\ cos\delta\ cosH - sin\delta)}{sin^2H + (tan\phi\ cos\delta - sin\delta\ cosH)^2} \end{aligned}$$

The constant, 15, converts the rate to degrees per hour. The second form of the equation enables the rate of field rotation to be found without having to find the parallactic angle.

Evaluating the derivative we find that the rate of field rotation peaks when the star crosses the meridian, i.e. when H = 0. Furthermore, the higher the star's culmination, i.e. the smaller the difference between δ and ϕ, the greater will be its rate of field rotation when it crosses the meridian. The maximum rate of field rotation, therefore, occurs when a star passes through the zenith. This implies that the worst time to observe a double is when it is best placed for observing! Consequently, there is a spherical cap around the zenith in which the rates of field rotation are too great to enable accurate measurements to be made. The size of this cap is largest at lower latitudes and smallest at higher latitudes, reducing to zero at the pole. Field rotation rates close to the zenith can reach hundreds of degrees per hour. However, such high rates can only be sustained for very short periods (as they clearly can not rotate more than 360°in 24 hours) after which they reduce to low rates again.

Conversely, the rate of field rotation is zero when the star crosses the prime vertical, i.e. when the star is due east and again when it is due west. Obviously, only stars with declinations that lie between the observer's latitude and the celestial equator will cross the prime vertical. Hence, the best times to observe double stars, as far as field rotation rates are concerned, are when the stars are in the eastern and western regions of the sky.

The average rate of field rotation is, not too surprisingly, the rate of the Earth's rotation, namely 15°per hour. This is half the rate of 30° per hour at which the hour hand of a clock turns. A rotation rate of 360° would be a very high rate, yet it is the rate at which the minute hand of a clock turns.

The problem, then, lies not in whether the rotation rate is too great to make a position angle measurement, but in whether the observation can be timed with sufficient accuracy, i.e. in recording the time when the companion was at that particular zenithal positional angle. For a star with a field rotation rate of 15°, the time of the zenithal position angle measurement would have to be made to an accuracy of 12 seconds; that is to say that the time will have to be noted within 12 seconds of having set the position angle on the micrometer if an accuracy of 0°.1 is to be achieved. This is because the zenithal position angle would have rotated 0°.1 in 24 seconds and consequently after 12 seconds the position angle will be nearer the next tenth of a degree. In practice one would set the positional angle and then note the time before taking the positional angle reading.

The rate of field rotation that can be tolerated will depend upon how accurately the observation can be timed. If it is done manually and we assume that the time can be read off the clock within 10 seconds of making the position angle setting then we have an upper limit on the rate of field rotation of 18° per hour. Field rotation rates less than this is typically found in the eastern and western sections of the sky. If the time is recorded electronically then much higher rates can be tolerated and the 'no go' area around the zenith could be reduced considerably.

The highest rate of field rotation, in degrees per hour, that can be tolerated is just 180° divided by the number of seconds it takes to note the time of the observation, or conversely, divide 180° by the field rotation rate to determine the time limit.

23.8.3 The Separation

. The separation can be made in the usual way. However, to make the double distance measurement set the fixed wires on the primary with the position angle wire bisecting the primary and the companion. Then move the moveable wire onto the companion. Note the reading on the micrometer screw. Now rotate the micrometer right around so that the position angle wire again bisects the primary and the companion, but the moveable wire is on the opposite side of the primary to the companion. Then move the moveable wire back, across the primary, to the companion again. Note the new reading on the micrometer screw. The difference between the two readings gives a measure of the double distance.

Ideally, the companion should be on the position angle wire when the separation measurement is made, but due to field rotation it might have moved away. The error this would induce would depend on the separation. The error is just ρ(1 - cos Δq), where ρ is the separation and Δq is the change in the parallactic angle. If, in the time it took to move the moveable wire on to the companion, the companion had moved two degrees it would induce an error of $0''.004$ in a separation of $10''$. As two degrees represents four minutes at a field rotation rate of 30°per hour field rotation would not be a major the source of errors in the separation.

23.8.4 Errors

Measurements of double stars made with an altazimuth mounted telescope are subject to the same errors as those made with an equatorially mounted one. However, additional errors can be introduced in converting the zenithal position angle to the position angle. The observer's latitude and the equatorial co-ordinates of the star are required to calculate the parallactic angle. The accuracy to which these are known determines the accuracy to which the parallactic angle can be calculated and in turn sets a limit on the accuracy of the position angle.

The errors in the parallactic angle would be negligible if the zenithal position angle was timed accurately and if the latitude could be determined accurately (perhaps from an accurate survey map or a GPS). Furthermore, precessing the right ascension and declination of the star from the catalogue positions would ensure accurate values for the co-ordinates of the star.

The separation, of course, will not be affected by these factors. Neither will the position angle if a mechanism that compensates for field rotation (a field de-rotator, as one manufacturer calls it) is fitted to the telescope. However such a compensating mechanism would, as it rotates, cause a right-angled eyepiece holder to ”fall over”, placing the eyepiece at an awkward angle. This would not be a problem if a right-angle eyepiece holder was not used, such as when viewing straight through the telescope or using a camera.

23.8.5 Computer programs

The formulae presented here are implemented in a suite of computer programs that can be found on the Springer website. Some additional programs are included such as calculating the visual aspect of a double star (Chapter 7) and the calibration of the ring and filar micrometers (Chapters 12 and 15).

Chapter 24
Catalogues

Bob Argyle

24.1 General Catalogues

24.1.1 Northern hemisphere

The first catalogue of double stars is due to Christian Mayer in 1779 and contains 80 entries. It was the work of Herschel and especially Struve who gave the whole subject a respectability which was lacking. Struve's 'Mensurae Micrometricae' (to give the catalogue its shortened name) which appeared in 1837, was a huge work in more than one respect. (The original volume is cm x cm and weighs in at some xx kg. The first 200 pages are also in Latin).

The next major catalogue did not come until 1906 when Sherburne Wesley Burnham produced his 'A General Catalogue of Double Stars within 121 degrees of the North Pole', published by The Carnegie Institute of Washington. It contains 13,665 systems and is unique in that it includes all known references to the measures contained within. It did, however, include some wide pairs which were not binary but optical in nature.

In 1932, Robert Grant Aitken produced the 'New General Catalogue of Double Stars within 120 degrees of the North Pole' with 17,180 entries. It is usually known as the ADS. The limits for inclusion were stricter than those of Burnham so Aitken's catalogue contains more true binary systems.

24.1.2 Southern hemisphere

By this time RTA Innes was in South Africa, having been appointed Director of the Transvaal Observatory and then the Republic Observatory. Innes, ably assisted by W.H. van den Bos and W.S.Finsen started on a new survey for double stars in the southern skies. As no catalogue of southern doubles existed at this time, Innes compiled the Southern Double Star catalogue in 1927 as a means of identifying new

Fig. 24.1 Julie Nicholas, formerly Librarian at the Institute of Astronomy with copies of Struves' first catalogue, the IDS (open on the desk) and the WDS (on CD-ROM). The latter could also contain every measure ever made.

double stars during the subsequent searches. This covered the zones –90 to –19 and contained 7041 systems.

In 1910 R.P.Lamont a wealthy industrialist and friend of the double star observer W.J.Hussey (who was latterly Director of the Observatory of the University of Michigan) had authorised plans for a large telescope for double star observation. Hussey planned to install it at Bloemfontein in South Africa to continue his own searches for new double stars. Tragically Hussey died in 1926 en route to South Africa but the project was taken over by R.A.Rossiter who stayed until 1952. Rossiter then compiled the Catalogue of Southern Double Stars, essentially a list of the pairs discovered by Rossiter and his assistants Donner and Jessup - more than 7,600 in the 24 years ending 1952.

24.1.3 All sky catalogues

The first all-sky catalogue of double stars did not appear until 1961. It is printed in 2 volumes as Volume 21 of the Publications of Lick Observatory and its formal title is

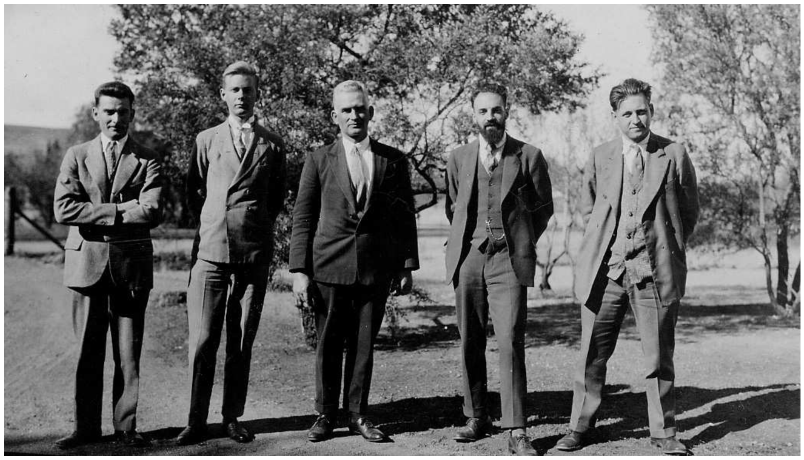

Fig. 24.2 These 5 observers were responsible for more than 10,000 double star discoveries. Pictured outside the Lamont-Hussey Observatory in Sept 1928 are (l. to r.) H.K.Donner, W.S.Finsen, R.A.Rossiter, W.H.van den Bos and M.K.Jessup

'Index Catalogue of Visual Double Stars 1961.0'. It is still the only printed version of an all encompassing catalogue and is now likely to remain so given that it runs to 1400 pages of closely printed script. Edited by Hamilton Jeffers, Willem van den Bos and Frances Greeby, the Index Catalogue of Double Stars or IDS was issued to include the large number of discoveries that had been made at the Republic and Lamont-Hussey Observatories in South Africa.

With the development of the Hipparcos project in the 1970's it was apparent that with the very approximate positions (0.1 minutes of time in RA and 1 - 2 arc minutes in Declination) and insufficient cross references between the IDS and other catalogues - largely the Durchmusterungs, it would be a disadvantage when programming the satellite to observe double and multiple systems. This led Jean Dommanget, a member of the INCS (Input Catalogugue) consortium and a well-known double star researcher at the Royal Observatory in Brussels to propose a new catalogue - the CCDM (Catalogue of the Components of Double and Multiple Stars) which would feature considerably better positions and photometry for the stars in the Hipparcos input catalogue (about 120,000) which were known to be double or multiple in question. More importantly it was necessary to list all the components of each system so that the new discoveries made by Hipparcos could be evaluated more easily. The purpose of the CCDM is to be complementary to the WDS. It does not aim to be all-inclusive but it does contain more detailed information on a smaller number of systems. In collaboration with Omer Nys, Jean Dommanget produced the first version of CCDM in 1994 and a second version is in preparation. It will contain about 45,000 systems.

The current version of CCDM can be found via the CDS at Strasbourg at http://cdsweb.u-strasbg.fr/cgi-bin/Cat?I/211 and a file of all the systems observed by the satellite which is essentially a subset of the CCDM can be found at http://cdsweb.u-strasbg.fr/cgi-bin/Cat?I/260.

The central data repository for visual double star data continues to be kept at the United States Naval Observatory. In the early 1960's the late Charles Worley received the Index Catalogue (in card form) from Lick Observatory which had appeared in 2 parts as described above. Copies of this catalogue were rarely seen except in the reference libraries of observatories so data on visual double stars was not easy to obtain at this time.

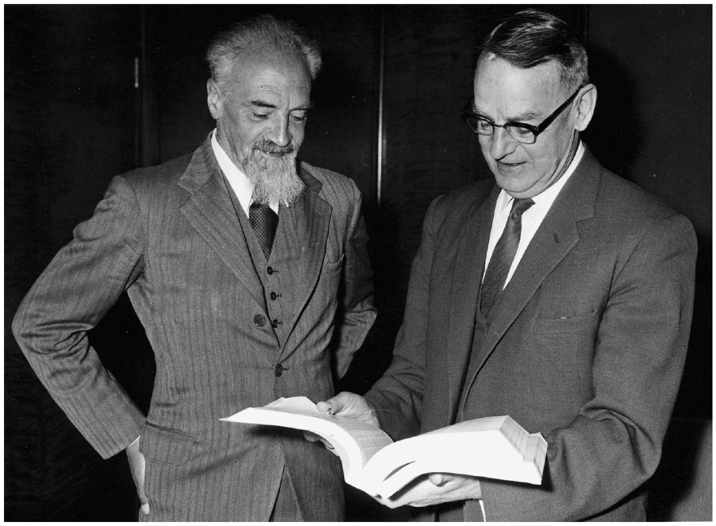

Fig. 24.3 Dr. W.H. van den Bos looks on proudly as the President of the South African Council for Scientific and Industrial Research, Dr. S. Meiring Naudé peruses a copy of the IDS (1968). (Copyright CSIR).

Worley, ably assisted by Geoffrey G. Douglass and others, spent the rest of his working career bringing the Lick Catalogue up-to-date. This meant, amongst other tasks, converting the punch cards into computer files, inputting new measures and discoveries on a regular basis and weeding out errors. The result of this was the first electronic version of the Washington Double Star Catalogue, WDS 1996.0 - so called because it represented the state of the data archive at the beginning of 1996. It had grown to some 78,000 entries so producing a printed copy was out of the question. After Worley's death the archive was taken over by Dr. Brian D. Mason who had done his research in the discipline of speckle interferometry at Georgia State University.

The current catalogue contains the new pairs discovered by the Hipparcos satellite and so offers double star observers a whole new set of pairs to measure. Most of these pairs have remained unobserved from the ground but it must be noted that many are very difficult and require both large apertures and good seeing.

The WDS catalogue can be downloaded from the USNO site at `http::/ad.usno.navy.mil/wds`

and at the time of writing (Mar 2011) it is 13.5 MByte in size and contains more than 113,000 entries. It is also available in portions of 6 hour intervals in RA. Another file contains useful notes on systems of interest. In addition there are two useful cross-reference files, for Hipparcos v HDS numbers (Hipparcos Double Stars) and WDS v ADS V BDS. Although the latter two reference numbers are not adopted in the current WDS, the ADS is still used by orbit-computers. The data is given in a rather compact form and so on first acquaintance it needs the use of the accompanying key to decipher what the data columns mean. The main advantage of the online WDS is that it is not only obtainable by anyone (try finding a copy of the IDS!) but it is a **dynamic** database and is updated nightly!

For those not on the Internet then rgw WDS 2006.5 CD-ROM can be obtained directly from USNO (the name and address is in the Appendices). Although this includes the WDS catalogue, the 5th orbit catalogue and the 3rd Interferometric Catalogue it cannot include the regular updates for which an Internet connection is required.

Whilst the WDS catalogue is large, it is dwarfed by the Observations Catalogue which is also maintained by USNO but which is not generally accessible. At the time of writing (MaR 2011) this consisted of 920,263 mean observations of 113,000 pairs. Genuine requests for data need can be made using the request form on the web site. This is particularly useful for orbit determinations for instance. Dr Mason has written a very useful guide to the the WDS and associated catalogues which can be found in Mason (2009). It is freely accessible on-line.

24.2 Interferometric data

On the USNO website there is also a separate database made up of all observations made by interferometric techniques whether it be speckle, ground-based arrays or even the early Michelsen Interferometer observations at Mount Wilson. The common property is that the accuracy is extremely high and this is an ideal source of useful data for those who want to test the quality of their telescopes. The author has selected several hundred pairs from this list which show very little motion and thus can be used as a resolution test. The separations range from 0.2 to 2 arc seconds. These lists can be found in Chapter xx.

Perhaps a more useful set of measures for those with a small telescope is those made by the USNO Astrometry Department using a speckle interferometer on the 26.5-inch refractor at Washington. Since 1990 and again under the direction of Charles Worley, and more recently, Brian Mason, an extensive programme of measurement of brighter binaries has been undertaken and the results have appeared in numerous papers in the Astronomical Journal and Astrophysical Journal Supplements.

24.3 Double star nomenclature

Many observing guides tend to use the old catalogue names for double stars some of which use Greek letters, i.e. β for Burnham, ϕ for Finsen and so on. This has nothing to do with the Flamsteed letters such as δ Equulei but the current nomenclature in the Washington Double Star catalogue avoids such possible complications and tends to be favoured by the professional observers. In this scheme the star is referred to by its J2000 coordinates. Thus as an example we can take Castor which is Σ1110 (Σ being the Struve catalogue) but appears in the WDS catalogue as STF1110 where the discoverer is denoted by one, two or three letters and avoiding Greek names altogether. The WDS name for Castor is thus WDS07346+3153.

At the time of writing in the first edition (2004) a decision to replace the current WDS with an enhanced one to include not only visual double stars but spectroscopic pairs and exoplanets has been made. A scheme based on a modified WDS is being prepared but it is not yet ready

In some cases the ADS (or Aitken Double Star catalogue number) is still used but this system is no longer supported by the WDS, partly because it includes only 20% of all known pairs. References to the Burnham Double Star Catalogue (BDS) numbers are also occasionally to be found but again not in the WDS. For more details of these catalogues see Chapter 24. The WDS website contains a cross-reference file which allows checking between WDS, BDS and ADS.

The short list below can be used to cross-reference the usual nomenclature in observing guides with the WDS system which is three letters and 4 numbers, with blanks being significant, so if you wish to search the WDS for Dawes 4 then you need to look for the string DA$\nabla\nabla\nabla\nabla$ where each ∇ represents a blank.

Table 24.1 Some common double star discoverer designations

Discoverer	Usually	WDS
Aitken, R. G.	A	A$\nabla\nabla$
Burnham, S, W.	β	BU∇
Struve, F, G. W.	Σ	STF
Struve Appendix Catalogue I	ΣI	STF
(with note) Struve Appendix Catalogue II	ΣII	STF (with note)
Struve, Otto	$O\Sigma$	STT
Pulkova Appendix Catalogue	$O\Sigma\Sigma$	STT (with note)
Finsen, W.	ϕ	FIN
Dunlop, J.	Δ	DUN
Herschel, W.	H I, II etc	H$\nabla\nabla$ (with note)

Chapter 25
Publication of results

25.1 Introduction

Publishing observations of double stars is a natural consequence when an observer feels confident enough in the quality of his or her measures that they it is time to share them with the rest of the astronomical community. A lot of effort has gone into this work so it is only fair that the observer should gain credit for it. There is no fixed formula which can be applied to decide whether measures are of publishable quality or not. But recent lists of bright, close (0.5 to 2 arc sec) pairs (Worley et al) are available so some comparison can be made to check on how good the agreement is. Other factors to consider include whether a particular pair has been observed many times or virtually ignored since discovery. A really accurate measure of a bright, relatively fixed, overobserved pair is probably not going to be as useful as a less accurate measure of a pair which has been ignored for 100 years or more. If it turns out that the latter has significant motion then this will be the more useful observation.

Measures can be published in several formats and in both professional and amateur journals but one thing cannot be overemphasized. It is absolutely vital that the same measures are never published more than once. This is not only a pointless exercise but it can cause great confusion to the astronomers who collate all measures of visual binary data for the Observations Catalogue at the USNO in Washington.

The paper should contain details of the micrometer type, the instrumental constant and the magnification employed.

The format of any list should contain the following information:

25.1.1 Identifier:

Currently the standard is the WDS format (see Chapter 24). This is also includes the J2000 position.

25.1.2 Catalogue:

An alternative identification, not always necessary but it can be useful when using Star Atlases and catalogues such as Burnham, Webb's Celestial Objects and the Sky catalogue 2000.0.

25.1.3 Mean position angle:

This should be the mean value from the individual nightly values. Quoted to 1 decimal place. Avoid using angles greater than 360.0. This was in vogue in Victorian times.

25.1.4 No of PA measures:

The number of independent nights from which the mean is formed. This will usually be the same as the number of nights used for the mean separation

25.1.5 Mean separation:

In arc seconds, usually quoted to two decimal places - if the observer considers this to be a fair reflection of the scatter in the individual measures

25.1.6 No of separation measures:

As for position angle. It may be for a highly inclined binary where the change is nearly all in separation that more measures in separation would be a sensible approach.

25.1.7 Mean epoch:

This is much easier to work out if each individual night is converted to a decimal of a year in the observing log. A day is 0.0027 of a year so midnight on 2001 Jan 10, for example, is 2001.027. It is quite sufficient to use the midnight value for that night and in fact mean epochs can be quoted to 2 decimal places for most small telescope observations. See Appendix I for a ready table.

25.1.8 Observer:

This will usually given at the head of the paper for a single author. Usually a two letter code is inserted at the end of each line in the data table if the list contains the measures of more than one observer. Those whose measures are included in the WDS Observations Catalogue are given a three letter identifier by the compilers.

25.1.9 Orbit residuals:

The differences (observed-computed) for both position angle and separation from the orbit for every epoch of observation. Include the author of the orbit and its date of publication. Include other orbits if there is little to choose between them. See Chapter xx for sources of orbital elements.

The following data can be given depending on taste:

(i) Difference in magnitude: Usually estimated visually to 0.1 magnitude.

(ii) Standard error of position angle and separation. Calculated from the individual measures that make up the means.

(ii) A note of whether the eyes were vertical to the wires (:) or parallel to the wires (..) when the observations were made.

(iv) The quality of the night - transparency and seeing, for instance.

Chapter 26
Appendix Brief biographies

Bob Argyle

26.1 Andreas Alzner

After studying physics and astronomy in Bonn, Andreas completed a dissertation in nuclear physics in 1985 and followed this with work in the electrical industry as technical instructor for magnetic resonance imaging systems where he remains.

His early interest in amateur astronomy from 1968 to 1992 consisted of observations with reflectors (4.5-inch, 6-inch, 8-inch, 14-inch) and refractors (5-inch, 6-inch), but (he says) nothing scientific. He was interested in double stars from the beginning on but his telescopes were never good enough for measurement work.

His first really good telescope, a 14-inch Zeiss Newtonian, was acquired in 1992 followed in 1996 with a long-focus 13-inch Cassegrain. Since then he has made several thousand measures with with filar and double image micrometers and has also published a number of orbits in Astronomy and Astrophysics and the Circulars of IAU Commission 26.

26.2 Rainer Anton

26.3 Graham Appleby

Graham Appleby spent his working life on various projects at the Royal Greenwich Observatory in Herstmonceux and at Cambridge until its closure in 1998. At that time he transferred to the Natural Environment Research Council where he continues to work within the Space Geodesy Facility. He has a Mathematics BSc and an Aston University PhD in Satellite Laser Ranging. Graham has long been interested in the lunar occultation technique, having made a large number of visual observations and carried out various scientific analyses. He is currently involved in using the SLR system to make high-speed photoelectric observations of occultations for double star and stellar diameter determination.

26.4 Bob Argyle

His blinkered interest in double stars dates back to the late 60s and a period at the Royal Greenwich Observatory at Herstmonceux in 1970 when he was let loose on the 28-inch refractor only made it worse. Occasional and all-too-short periods of observing occurred until 1990 when the RGO moved to Cambridge and Bob along with it. The availability of the 8-inch refractor satisfied a long-desired need for regular observation which is still in progress today. Bob retired from the Institute of Astronomy in 2010, but he remains a member of Commission 26 (Double Stars) of the International Astronomical Union and an Editor of 'Observatory' magazine. He is President of the Webb Society and has directed the Double Star Section since 1970.

26.5 Owen Brazell

As well as editing the Webb Society Deep-Sky Observer, Owen is also the assistant director of the British Astronomical Association's Deep-Sky Section and a regular contributor to Astronomy Now. When observing, his primary interests are in the observation of planetary and diffuse nebulae – although since the acquisition of a 20-inch Obsession telescope this has also moved to viewing galaxy clusters. His interest in astronomy was sparked by an attempt to see a comet from his native Toronto. From early years, he kept up his interest in astronomy which culminated in a degree in astronomy from St Andrews University in Scotland and taking though not completing an MSc in Astrophysics. At that time, he also gained an interest in the northern lights. As with many astronomers, finding no living there, he moved into the oil business first in R&D and then as a computer systems designer (this explains his interest in the computer side of astronomy). Despite this he still uses Dobsonian-type telescopes ranging from a 4-inch Genesis-sdf up to the Obsession. The recent plethora of fuzzy objects that move has re-awakened an interest in comets! His searches for dark skies have taken him from the mountains of Canada through Texas to the Florida Keys as well as to Wales - the only good dark sky site he has found so far in the UK.

26.6 Robert K. Buchheim

Bob Buchheim has been an avid amateur astronomer for over 30 years. His particular joys are introducing children to the night sky, and encouraging amateur astronomers to participate in small-telescope research projects. His book, ”The Sky Is Your Laboratory” is a manual for the research-oriented amateur astronomer. Mr. Buchheim has been a visual observer, telescope maker, CCD astrometrist and photometrist. He has published deep sky observations, presented papers at astronomy conferences, given presentations to amateur astronomy clubs, and published research papers on asteroids, variable stars, and double stars. He is a Trustee of the Orange County Astronomers (in southern California), a Board member of the Society for Astronomical Sciences, and proprietor of the Altimira Observatory (in his backyard). In 2010 he was awarded the G. Bruce Blair award for noteworthy contributions to amateur astronomy, by the Western Amateur Astronomers. His professional background is in engineering and manufacturing management; in that role has published a few technical papers in peer-reviewed journals. He received a BS in Physics from Arizona State University, and is a graduate of the Defense Systems Management College and the UCLA Executive Management program.

26.7 Rafael Caballero

26.8 Andreas Maurer

Andreas is a mechanical engineer and a lifelong astronomy enthusiast. Since his recent retirement, he is now able to concentrate on his astronomical interests. Besides activities related to the history of astronomy he is building his own telescopes and is restlessly experimenting with home-made auxiliary equipment suitable for amateur observations. Whenever nightly seeing conditions are favourable he observes double stars from his home in Switzerland.

26.9 Michael Ropelewski

Mike Ropelewski is an active member of the British Astronomical Association and the Webb Society. His main interests are the study of aurorae, comets, double stars and eclipses. His instrumentation includes 15 x 45 stabilised binoculars, a 102 mm SCT and a 250 mm Newtonian reflector in its own observatory. In 1999, the Webb Society published his first book entitled ‘A Visual Atlas of Double Stars’. During daylight hours Mike is a computer programmer/analyst by profession. Apart from astronomy, he enjoys gardening, music, poetry and steam railways.

26.10 Christopher Taylor

Originally trained as a theoretical physicist, Christopher Taylor teaches mathematics and astronomy over a wide range of undergraduate courses and is tutor on the University Department for Continuing Education’s long-running astronomy evening classes in Oxford. He is Director of the Hanwell Community Observatory, a public educational venture set up in partnership with the Oxford Department under the Royal Society's Millennium Awards Scheme. This will contain one of the largest telescopes in Britain wholly dedicated to public and educational astronomy, as well as other instruments from 4 to 30- inches aperture (0.1 to 0.76-m.) available for amateur research. Christopher Taylor has been an active observer since 1966, for most of that time using the same 12.5-inch (0.32-m.) reflector, with a long standing interest in visual binaries which has become his main observational pursuit since 1992. Motivated by the belief that the deepest satisfaction in practical astronomy is to be had from doing real science, other observational interests are high-resolution optical work in general (including, e.g., planetary), optical spectroscopy and broadly anything quantitatively measurable in the sky. For further information on the Hanwell Observatory see http://www.hanwellobservatory.org.uk.

26.11 Tom Teague

Tom Teague is a Fellow of the Royal Astronomical Society and a member of the Webb Society and the British Astronomical Association. He has written articles for Sky and Telescope, the Journal of the British Astronomical Association and the Webb Society Quarterly Journal, covering such topics as double-star micrometry, sunspot measurement and amateur spectroscopy.

26.12 Nils Turner

Nils Turner has been using speckle interferometry to observe binary stars on large telescopes since 1990. Since 1996, he has used adaptive optics to study binary stars, concentrating on the relative photometry as opposed to the astrometry. He is a member of the American Astronomical Society. By day (and night), he works in the field of optical/IR michelson interferometry. Outside of astronomy, Nils enjoys Linux programming, playing viola in a community orchestra, cycling, and playing Ultimate (frisbee).