Double Stars

Measurement of separation and position angle with small telescopes

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Table of contents

1 Double stars - A short introduction

A distinction is made between optical and physical double or multiple stars. The former are stars that only happen to be in a line of sight, but are far behind each other in three-dimensional space and are not gravitationally bound. Physical binary and multiple stars are gravitationally bound. The focus of this article is on physical binary and multiple stars, hereinafter referred to simply as binary or double stars.

Physical double stars can be divided into different categories. Visual double stars can be separated and measured with the naked eye or optical aids (binoculars, telescope).

Spectroscopic double stars are so close together that they can no longer be separated with optical aids, but are noticeable in the spectrum through Doppler shifts.

If we look directly at the edge of the orbit of double stars, this can lead to a mutual occultation of the stars, analogous to a solar eclipse. The occultations lead to periodic fluctuations in brightness, which reveal the nature of the double star. Pairs of stars of this type are also called eclipsing binaries.

Finally, there are astrometric double stars, which only reveal themselves in the course of time due to a non-linear movement in the sky. Single stars have a constant motion in the sky, while astrometric double stars fluctuate periodically back and forth in their motion. Fluctuations in movement drew the attention of astronomers to Sirius B, for example.

Double stars are generally described in various books on astronomy. A short introduction can also be found on the Internet at Wikipedia, for example. Also recommend is a book by *James Mullaney* which deals with double and multiple stars in great detail [2].

The double stars visible from Earth are initially recorded in two dimensions, as the sky above us is spherical. The actual three-dimensional arrangements and movements of double stars can also be determined if necessary, albeit in a much more complex way. This article is limited to the detection of double stars and measurements in two dimensions in the sky and not to the determination of orbital parameters in three-dimensional space.

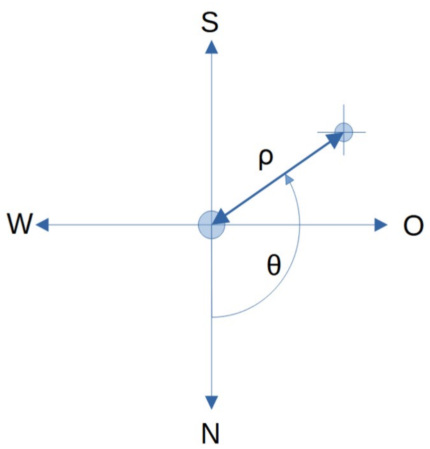


Illustration 1: Double star, view in an astronomical telescope

Basically, double stars are characterised by the separation ρ (RHO), the distance between the components and the position angle θ (THETA). The position angle is measured in degrees [°] from 0°..360°, starting in the north via east, south and west. The origin is the brighter component.

- (RHO) Separation/distance usually in arc seconds ["]
- (THETA) Position angle from north over east measured in degrees [°]

2 Measuring system for detecting double stars

A measuring system for recording the separation and position angle of double stars consists of a telescope, the mount and the detector. The focal length of the telescope and the optional additional optical components are decisive for the imaging scale.

Telescopes with a fixed focal length are advantageous in terms of determining the image scale. Systems with variable focal length, e.g. with primary mirror focussing, should be viewed with caution here, as the image scale can change, which has a negative effect on the calibration and precision of the measurements. In principle, refractors and also Newtonian or (classic) Cassegrain telescopes are well suited. In the case of refractors, it should be noted that these are sometimes affected by chromatic aberration, which can have an influence on the accuracy of the measurement results depending on the type of refractor (FH, ED, APO). With mirror telescopes, the effect of the secondary mirror mount must be considered. In the most unfavourable case, the spikes can cover a faint double star component.

An equatorial mount makes it much easier to determine the position angle, as one calibration per measurement campaign is sufficient. With an azimuthal mount, e.g. according to Dobson, the angle in the detector changes with time/earth rotation, which makes it much more difficult to calibrate the north-south direction and in principle requires recalibration for each measurement.

Historically, (filar) micrometers and astrometric eyepieces, e.g. the Baader/Celestron Micro-Guide eyepiece, were used for measurements. Today, the use of CCD or CMOS detectors is more modern and usually more accurate [13].

2.1 Measuring system used

2.1.1 Detector

In the further course of this article, either a simple ZWO ASI 120MC-S 1.2 megapixel (1280 x 960) CMOS USB 3.0 camera with square pixels of 3.75 µm or a monochrome ASI678MM USB 3.0 camera (3840 x 2160 pixels, 8.29 megapixels) with pixels of 2.0 µm will be used as the detector. It is advisable to verify the pixel size specified by the camera manufacturer using the data sheet of the light-sensitive chip used. As a rule, the capture area is reduced to 800 x 600 pixels during observation in order to reduce the data volume and speed up processing later.

2.1.2 Telescope

A 120/900 mm Skywatcher/Equinox ED APO is used for measurements. To facilitate the final adjustment to the centre of the detector, a 60/800 mm guide scope is optinally mounted parallel to the Equinox. The guide scope is equipped with the Baader Microguide measuring eyepiece and thus allows the exact alignment of the double star at a magnification of 64x.

A Scheiner (Hartmann) aperture diaphragm is used for precise focussing at the start of a measurement campaign. This aperture diaphragm consists of three holes, each with an aperture of 40 mm, which are offset by 120° around the optical axis. Due to the selected magnification, focussing can also be performed directly on a suitable star using the camera's live view function.

2.1.3 Mounting and control

A Vixen GPD2 equatorial mount is used together with a Boxdörfer controller, which allows GOTO. The GOTO function in combination with the guide scope and a LED star finder is sufficiently precise for finding double stars.

2.2 Use of filters

Some articles on the net recommend the use of filters when measuring double stars. With refractors, for example, green, yellow, red, (infrared) or even line filters (Baader solar continuum / 540 nm) can reduce or completely avoid possible errors due to chromatic aberration and atmospheric dispersion.

Filters also have an influence on the resolution. In principle, the resolving power depends on the wavelength used and is slightly higher in the short-wave blue range than in the red range. However, it must be taken into account here that refractors in particular are often less well corrected in the blue range, with the exception of (full) APOs.

For the classic Fraunhofer reference lines, this results in the following resolving power using the 120/900 mm Skywatcher Equinox as an example.

Fraunhofer line	Colour	Wavelength [nm]	Resolving power ["]
F'	Blue (B)	480	1,01"
n_e	Green (G)	546	1,14"
C'	Red (R)	644	1,35"

- Wavelength-dependent resolving power according to Rayleigh on the 120/900 Equinox -

Depending on the focal length and focal ratio, FH refractors in particular can show significant residual chromaticity (RC), which can lead to deviations in measurements. With colour cameras, it may be worth splitting the sum image into the individual R-G-B components and measuring these separately.

Certain colour filters can reduce or even completely eliminate atmospheric dispersion, which can introduce a considerable measurement error. In the red and infrared range, seeing does not have as strong an effect as in the visible and blue-green range. Despite the somewhat lower resolution in this range, better measurement results may be achieved with red or infrared filters.

3 Resolution & image scale

3.1 Resolving power

The resolving power of a telescope essentially depends on the diameter of the airy disc (D_{Airy} / δ_{Airy}), which is calculated in metres or arc seconds as follows:

$$D_{Airy} = \frac{2{,}44 \cdot \lambda \cdot f}{D} = 2{,}44 \cdot \lambda \cdot N$$

D_{Airy} [m] D=aperture [m] / λ=wavelength [m] / f=focal length [m]

$$\delta_{Airy} = \frac{2{,}44 \cdot \lambda}{D} \cdot 206265$$

δ_{Airy} [“] D=Aperture [m] / λ=Wavelength [m]

Basically, there are now two common approaches to determining the resolution of a telescope: the Rayleigh criterion and the Dawes limit. According to Rayleigh, the centers of the two Airy disks are separated by a distance of D/2, as shown in the image below. The intensity of equally bright components decreases by approximately 27% (~30%) between the two components.

$$\alpha = \frac{1{,}22 \cdot \lambda}{D} \cdot 206265 = \frac{0{,}1384}{D}$$

α [“] D=aperture [m] / λ=wavelength [m] (550 nm)

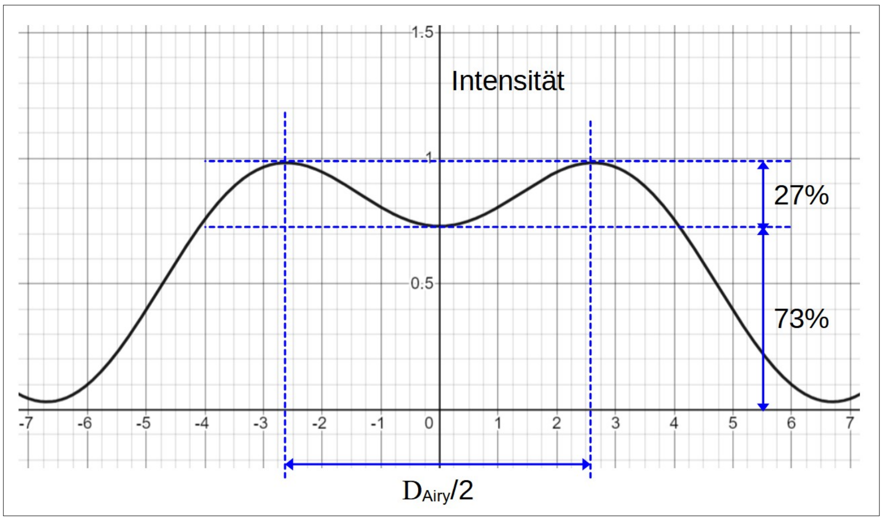


Illustration 2: Rayleigh criterion - Created using desmos [13]

Under good conditions, however, the human eye can still recognise differences in brightness of around 5% between two (equally bright) components. This corresponds to the resolution according to Dawes and is calculated approximately as follows:

$$\alpha = \frac{1{,}02075 \cdot \lambda}{D} \cdot 206265 = \frac{0{,}1158}{D}$$

α [“] D=aperture [m] / λ=wavelength in [m] (550 nm)

3.1.1 Resolving power 120/900 Equinox

Diameter of the airy disc in [m] or [µm] :

$$D_{Airy}=\frac{2{,}44\cdot\lambda\cdot f}{D}=2{,}44\cdot\lambda\cdot N=2{,}44\cdot 550\cdot 10^{-9}\cdot 7{,}5=0{,}000010065[m]=10{,}065[\mu m]$$

Angular expansion of the airy disc (from zero to zero) in arc seconds :

$$\delta_{Airy}=\frac{2{,}44\cdot\lambda}{D}\cdot 206265=\frac{2{,}44\cdot 550\cdot 10^{-9}}{0{,}12}\cdot 206265=2{,}306''$$

Resolution in arc seconds according to Rayleigh :

$$\alpha=\frac{1{,}22\cdot\lambda}{D}\cdot 206265=\frac{1{,}22\cdot 550\cdot 10^{-9}}{0{,}12}\cdot 206265=1{,}15''$$

according to Dawes :

$$\alpha=\frac{0{,}1158}{D}=\frac{0{,}1158}{0{,}12}=0{,}97''$$

3.1.2 Other influencing factors

In practice, however, other factors come into play that determine the actual resolving power of a telescope. Depending on the factor, this can also lead to a higher resolution than was actually expected based on the equations above:

- (Different) brightness of the components involved
- Colour of the components involved
  - wavelength-dependent resolution of the telescope
  - Wavelength-dependent size of the Airy disc
  - Wavelength-dependent sensitivity of the human eye during visual observation
  - Atmospheric dispersion
- **Perception threshold** of the human eye during visual observation [9]
  - Fainter stars have a smaller airy disc
  - The visual resolution increases with fainter stars
- Magnification of the telescope
  - Empirical studies have shown (Couteau [1]), that the useful **minimum** magnification for double star observations corresponds to twice the objective diameter in millimetres
- Obstruction of the telescope
- Use of lens masks (Gauss masks)

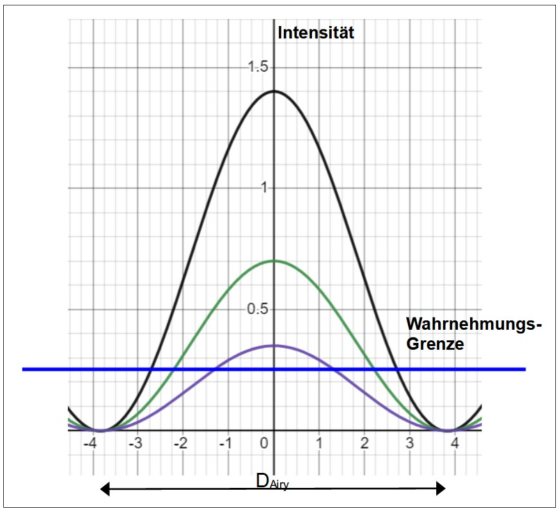


Illustration 3: Created using desmos [13]

3.2 Image scale

The angle per pixel that is imaged on the detector is calculated as follows:

$$\alpha = \frac{206{,}265 \cdot P_s}{f}$$

P_s - pixel size in [µm] / f - focal length in [mm] / α - arc seconds ["/pixel]

This leads, for example, to the following image scales with the above-mentioned SW Equinox in combination with the ZWO ASI 120MC-S or ASI678MM at 900 mm focal length:

$$\alpha = \frac{206{,}265 \cdot 3{,}75}{900} = 0{,}86 \quad [\text{“/Pixel}]$$

$$\alpha = \frac{206{,}265 \cdot 2{,}0}{900} = 0{,}46 \quad [\text{“/Pixel}]$$

The following image scales ["/pixel] result for the actual focal length determined in chapter 4.3:

Primary focus ASI120 :

$$\alpha = \frac{206{,}265 \cdot 3{,}75}{901{,}3} = 0{,}8582$$

Primary focus ASI678 :

$$\alpha = \frac{206{,}265 \cdot 2{,}0}{901{,}3} = 0{,}4577$$

However, this is not yet the optimal image scale for these combinations for measuring double stars. See also the next chapter.

3.3 Optimum image scale for double star measurements

The optimum image scale for double star measurements is different from that of conventional astrophotography. The aim with double star measurements is to achieve sufficiently large 'centroids' for the measurement. Below is the derivation of the optimum image scale for the 120 mm Equinox ED APO. The diameter of the Airy disc according to 3.1 is δ_{Airy} = 2.307" or the radius r_{Airy} = 1.153" arc seconds.

$$\delta_{Airy} = \frac{2{,}44 \cdot 550 \cdot 10^{-9}}{0{,}120} \cdot 206265 = 2{,}307\,''$$

According to [11], the intensity curve of the diffraction disc and the diffraction rings follows a Bessel function of the first kind:

$$J(x) = \left(\frac{2}{\pi \cdot x} \sum_{m=0}^{100} \frac{(-1)^m}{m!(m+1)!} \left(\frac{\pi \cdot x}{2}\right)^{(2m+1)}\right)^2$$

(Bessel function 1st kind)

- x = 0 - has the function value 1
- x = 0.5145 - has the function value 1/2 (50 % of the intensity) → FWHM point
- x = 1.2197 - has the first zero

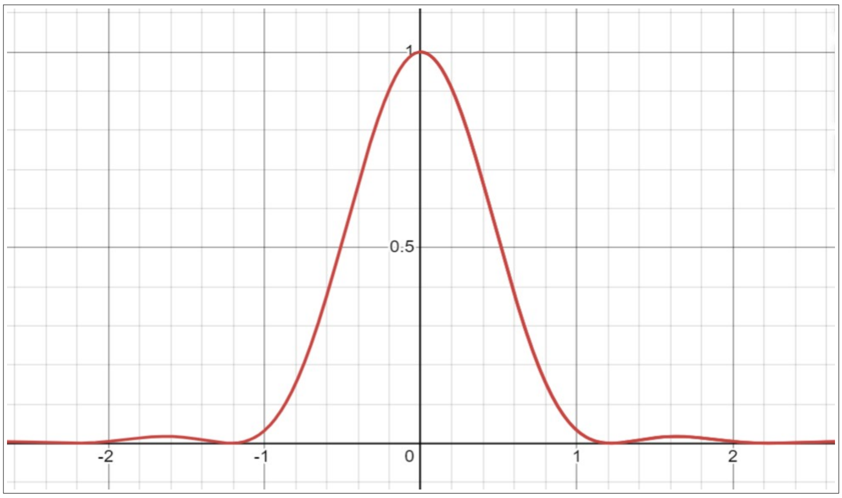


Illustration 4: Bessel function 1st kind - Created using desmos [13]

The first zero point is therefore reached at r_{Airy} = 1.153" (=> value 1.2197 of the Bessel function). The point of the Bessel function at which 50% of the intensity is reached is calculated as :

$$R_{FWHM} = \frac{1,153}{1,2197} \cdot 0,5145 = 0,457''$$

R_{FWHM} multiplied by two obtains the D_{FWHM} value for the 120/900 mm Equinox = **0.915"**

According to [1 / 15.4.1.1], one pixel should cover about 0.25 D_{FWHM} of the PSF generated by the lens. This results in an **optimum image scale of 0.23"/pixel** for the 120 mm ED APO mentioned above.

With the primary focal length of 900 mm, an image scale of 0.46"/pixel is achieved with the ASI678.

However, it should be noted that with increasing focal length, the light from the stars is distributed over more and more pixels, which reduces the achievable limiting magnification. For this reason, we aim an image scale of around **0.40"/pixel**. This is approximately achieved with the ASI678 in the primary focus.

3.4 Separability of double star PSFs

If stars are closer than 2 x FWHM, it becomes difficult to calculate the double star parameters reliably. The usual centroid algorithms, e.g. in AIP4Win, tend to have problems, as there is no longer a clear separation between the two components or their PSFs.

For the 120 mm ED APO, the limit here is $:\alpha = 0,915 \cdot 2 = 1,83 \approx 1,8''$

→ Narrower double stars can usually no longer be reliably calculated with AIP4Win.

According to [1 / 15.3], **REDUC** [12] is the only software that is able to reliably measure even closer pairs of double stars via so-called "surface" routing, especially those whose PSFs overlap.

4 Measurement errors

4.1 Influence of the focal length on the measurement accuracy

The nominal focal length of a telescope/lens is specified by the manufacturer, e.g. 900 mm. However, this focal length is subject to certain unfortunately unknown tolerances, i.e. the actual focal length will generally deviate more or less from the nominal focal length. According to the equation in the previous chapter, this results in a systematic measurement error.

Using the example of a nominal focal length of 900 mm and actual assumed focal lengths between 870..930 mm, the measurement error is determined here using the equation above for a double star with 10" distance for the ZWO ASI 120MC-S:

Actual focal length [mm]	magnification ["/pixel]	Measured distance	Deviation from the actual distance of 10"
880	0,879	10,23"	+ 0,23"
890	0,869	10,11"	+ 0,11"
900	0,859	10,0"	0"
910	0,850	9,89"	- 0,11"
920	0,841	9,79"	- 0,21"

- Dependence of the measuring accuracy on the focal length -

It is immediately apparent from the above that the accuracy of the determination of the actual focal length and thus the image scale is essential for the achievable measurement accuracy.

4.2 Exact determination of the focal length of a refractor

For telescopes or lenses, the focal lengths stated are nominal nominal focal lengths (manufacturer's specifications). There are tolerances in the manufacture of lenses, and the actual focal length of a lens can/will generally deviate slightly from the nominal focal length. These deviations from the nominal focal length introduce a measurement error that is difficult to calculate.

It therefore makes sense to determine the exact focal length of the lens used in advance for precise double star measurements. If this can be determined to an accuracy of ± 5 mm with the 120/900 ED-APO, for example, the resulting measurement error is sufficient for double stars up to ~30" distance.

4.3 Bessel method

Comparative studies [7] have shown that determining the exact focal length of a refractor is easiest and can also be done relatively accurately using Bessel's method [8]. If carried out accurately, the focal length can be determined with an accuracy of a few millimetres.

However, it should be noted that, strictly speaking, this only applies to 'thin' lenses. In the case of telescope lenses, the focal length is too high due to the lens thickness using the formula below. The deviation is >= +1% of the nominal focal length.

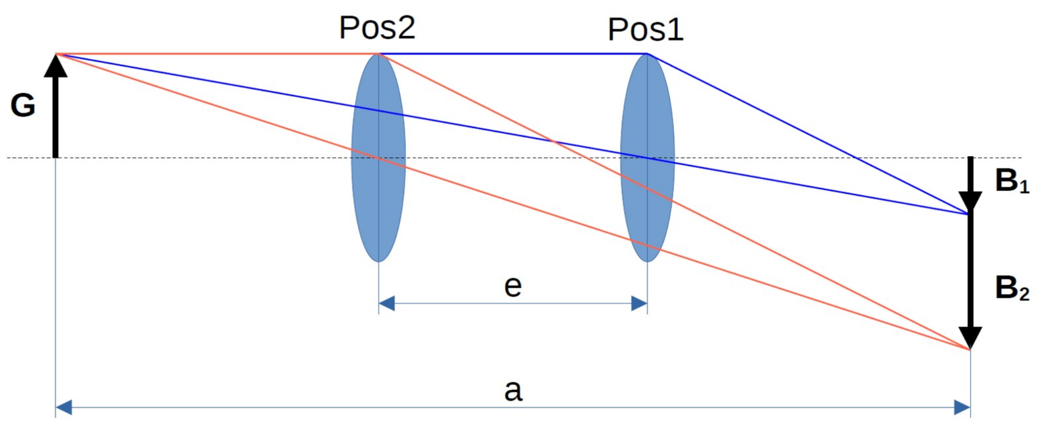


Illustration 5: Bessel method for measuring the focal length of a lens

In the Bessel method, an object **G** is imaged through a lens. There are two possible lens positions (**Pos1** and **Pos2**) where the object is in focus, **B1** (smaller) and **B2** (larger). In order to achieve sufficient accuracy, the distance 'a' between the object and the image should be at least four times the focal length of the lens.

The object **G** can be a bright lamp, which is positioned behind the focuser. Opposite the lens is a screen or simply a white wall onto which the image of the lamp is projected.

The lens is now moved until a small, sharp image is visible on the screen. The distance between the screen and the lens surface is measured (e1). Now move the lens further in the direction of the object/lamp. A large, fainter and sharp image of the object/lamp now appears at a certain position. The distance to the screen is measured again (e2). The distance between the two lens positions is now **e = |e2 - e1|**.

The focal length of the lens is then calculated as follows:

$$f = \frac{a^2 - e^2}{4 \cdot a} \qquad a \geqslant 4 \cdot f$$

If the distance measurements are carried out with sufficient precision, the focal length of the lens can be determined with a fairly high accuracy of a few millimetres.

4.3.1 Determining the focal length of the SW Equinox according to Bessel

In several measurements according to Bessel as described above, the focal length of the SW Equinox 120/900 mm was determined to be → **910 mm (± 2 mm)**.

However, the focal length determined above is about 1% too high due to the geometric thickness of the objective lens(es) HH' of the Equinox, which was not taken into account. Under the (realistic) assumption of an objective lens thickness HH' = 30..40 mm, the actual focal length of the Equinox is calculated as :

$$f = \frac{(a - HH')^2 - e^2}{4 \cdot (a - HH')} \qquad a \geqslant 4 \cdot f$$

Assuming an optical thickness of 30 ... 40 mm, the focal length of the SW Equinox 120/900 according to Bessel is → **900 mm (± 5 mm)**

As soon as the geometric thickness of the objective cannot be determined exactly, a more precise determination of the focal length is recommended, e.g. using the Baader Microguide eyepiece.

4.4 Focal length determination using Baader Microguide eyepiece

The average transit time of the linear scale of the Microguide eyepiece was determined in 5 to 10 runs. The scale has a length of exactly 6 mm. The focal length is calculated using the transit time (t) as a function of the declination of the measuring star.

$$f=\frac{82281}{t\cdot\cos(\delta)}$$

t - transit time [s] of the 6 mm in the microguide (60 ST) / δ - declination of the star

Derivation :

Field of view in arc seconds : $\alpha=15{,}0411\cdot t\cdot\cos(\delta)$ t – transit time [s] δ – declination

Image scale for 6 mm : $f=\frac{206265\cdot 6\,mm}{\alpha}$

Focal length : $f=\frac{206265\cdot 6\,mm}{15{,}0411\cdot t\cdot\cos(\delta)}=\frac{82281}{t\cdot\cos(\delta)}$

4.4.1 Equinox 120/900

ε Orionis (-1,18°) n = 5 $\bar{t}=91{,}31$ [s] σ_{tn} = 0,0864 $2\sigma_{tn}$ = 0,0965

Primary focal length : $f=\frac{82281}{91{,}31\cdot\cos(-1{,}18°)}=\mathbf{901{,}3}\,mm$ *[± 1 mm]* *(± 0,1 seconds)*

For use in primary focus, the following image scales result for a 3.75 µm sensor (ASI120MC):

Time [s]	Focal length f [mm]	Image scale ["/pixel]	Δα ["/pixel]
91,3964	900,4561755	0,859002105	+ 0,000812043
91,31	901,3082116	0,858190062	
91,2236	902,1618616	0,857378019	- 0,000812043

For use in primary focus, the following image scales result for a 2.0 µm sensor (ASI678MM):

Time [s]	Focal length f [mm]	Image scale ["/pixel]	Δα ["/pixel]
91,3964	900,4561755	0,458134456	+ 0,000433089
91,31	901,3082116	0,457701366	
91,2236	902,1618616	0,457268277	- 0,000433089

➔ The plate-scale error in both cases is → **Δα ~ ± 0,001 [“/pixel]**

With a maximum deviation/error of ~0.001"/pixel for the two extreme values and a target measurement accuracy of ± 0.1", the components of a double star may now have a maximum distance of ~100" from each other, otherwise the measurement error may be greater than 0.1".

4.4.2 Williams 80/545 :

Primary focal length : $f = \frac{82281}{150{,}3 \cdot \cos(-1{,}18°)} = \underline{547{,}6}\,[mm]$ [± 1.5 mm] (± 0.33 seconds)

4.5 Determining the focal length using a reference double star

In principle, the formula in (3.2) can also be used to determine the effective focal length of the optical system itself. This requires the distance ρ of a reference double star with exactly known separation, the measured distance of the two components in pixels and the pixel size of the detector:

$$f = \frac{P_{cou} \cdot P_s \cdot 206{,}265}{\rho}$$

f – focal length in [mm]

ρ - Distance in arc seconds of the reference double star
P_{cou} - Number of pixels between the two components, e.g. from AIP4Win
P_s - Pixel size in [µm] of the chip used

Example STF 1744 : P_{cou} = 50.71 pixels from AIP4Win, P_s = 3.75 µm, ρ = 14.5", 3x drizzle in AutoStakkert!

$f = \frac{50{,}71\,Pixel \cdot 3{,}75\,\mu m \cdot 206{,}265}{14{,}5''} = 2705\,[mm]$ due to 3x drizzle → **focal length = 901.7 [mm]**

4.6 Atmospheric refraction

The atmospheric refraction basically affects both/all double star components equally or very similarly due to the proximity of the components. In fact, there is also differential atmospheric refraction. If both components are vertical to each other, the lower component is more affected by atmospheric refraction than the slightly higher one. However, the effect can be neglected if the double star is higher than 30° in the sky. According to [1], the differential refraction between the components is then ≦ 0.1".

4.7 Seeing

The seeing also has an effect on the distance of the components, as the components can be subject to different seeing influences depending on the distance and the telescope used. This can cause the distance and/or the position angle to fluctuate. However, this effect is averaged out with longer exposure times and thus disappears almost completely. With an exposure time of more than a few seconds or when stacking a corresponding number of shorter-exposure images, this error is also reduced empirically to ≦ 0.1".

4.8 Atmospheric dispersion

Atmospheric dispersion is the wavelength-dependent atmospheric refraction of (star) light. Depending on the zenith position of the double star, this can introduce a considerable error. In [1], a double star pair was described as an example, consisting of a monochromatic red and a blue component at a distance of 50° from the zenith. The measurement error introduced in this case by atmospheric refraction is ± 0.5" ... 1.5", i.e. a considerable error with a desired measurement accuracy of ~ 0.1".

This effect is partly cancelled out by the fact that stars generally never emit only red or blue light, but always emit a continuous spectrum. However, this effect can only be completely avoided by measuring double stars when they are close to the zenith or by using filters. The best results are achieved here with narrow-band filters, which only allow a small section of the spectrum to pass through, but with the disadvantage that light of other wavelengths is lost and must therefore be exposed for longer.

The table below shows the calculated relative dispersion for various filter configurations. The calculations were performed using the tool *Refract.exe* [19], assuming a temperature of 15 °C, a pressure of 100 kPa, and a star elevation of 45°.

Filter-Configuration	Wavelengths	Relative Dispersion
Without filter	350-950 nm	1.635"
UV/IR cut	420-685 nm	0.808"
GG495+UV/IR cut	485-685 nm	0.478"
VG6	460-585 nm	0.411"
CMOS Green	490–580 nm	0.270"
OG570+UV/IR cut	565-685 nm	0.223"
RG610+UV/IR cut	620-685 nm	0.104"
Astronomik OIII (10 nm)	495-505 nm	0.037"
Baader Solar Continuum (10 nm)	535-545 nm	0.029"

4.9 Systematic error in AIP4Win

The Mizar calibration image shown below was measured a total of 10 times with AIP4Win under identical conditions in order to determine the systematic error of AIP4Win for this configuration.

```
AIP4Win v.2.4.10 Distance Tool
Date / Time: 2022-06-15 / 21:52:10
No plate solution available for this image.
Output values based on user input values.
User supplied focal length: 910
User supplied parallactic angle: 0.000 deg
User supplied pixel width: 0.00375 mm
User supplied pixel height: 0.00375 mm
```

The standard deviations were determined for the measured distances and position angles:

σ_θ = 0.023 " **σ_ρ = 0.0061°**

➔ The measurement error introduced by AIP4Win is considerably lower than the target measurement accuracy of ± 0.1". This results in a very high reproducibility and accuracy of the measurements.

4.10 Image field curvature

Another factor that can influence the measurement accuracy is a possible image field curvature or general imaging errors of the optics used, which can influence the image scale. These must and can only be determined empirically.

For this purpose, a reference double star is positioned and measured at at least three different locations in the detector, e.g. in the centre of the detector and in two different corners. The separation and the position angle are then determined and compared with each other.

Influences due to imaging errors of the optics used should become visible with this measurement.

4.11 Polar Alignment

The exact or non-exact alignment of the parallactic mount on the north celestial pole leads to image field rotation and therefore has an influence on the accuracy of the measurements of the position angle of double stars. The closer the double star is to the north celestial pole and the less accurate the polar alignment is, the greater this influence is and, in extreme cases, can lead to deviations of several degrees in the position angle.

This error can be counteracted by the following measures:

- Polar alignment as precise as possible
- The reference double star(s) should be close to the double stars to be measured

4.12 Excursion into the standard deviation

A brief excursion into statistics. Determining the standard deviation (σ) and the variance (2σ) are important tools for assessing the error of a measurement, as they show the spread of the measured values around the mean value μ, assuming that the measured values follow a normal distribution.

The standard deviation (± σ) defines a range where 68.2% of the measured values lie, provided the measured values follow the normal distribution shown below. The variance (± 2σ) is the square of the standard deviation, within which 95.4% lie.

The determination of standard deviation and variance only really makes sense with a sufficiently large sample, at least 10 measurements should be available, more is better.

The standard deviation can be calculated with any better pocket calculator or with Excel or LibreOffice.

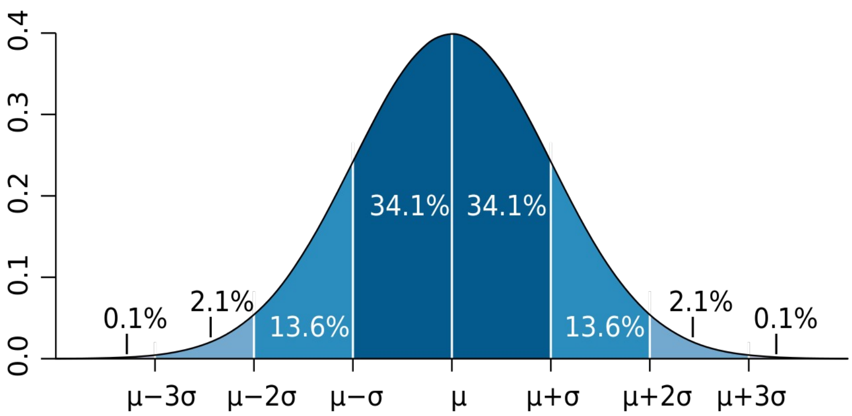


Illustration 6: Distribution of measured values - Source : [6]

5 Baader Micro-Guide measuring eyepiece

The Micro-Guide eyepiece from Baader Planetarium is a special illuminated measuring eyepiece with a focal length of 12.5 [mm], which unfortunately can only be purchased on the second-hand market. Various scales are used to determine distances and position angles. The achievable accuracy is primarily dependent on the focal length of the telescope and therefore on the magnification achieved. According to [5], higher accuracies can now be achieved in comparison with CCD or CMOS cameras. However, the micro-guide eyepiece can be used very advantageously, for example, to determine the exact focal length of the telescope, see also Chapter 4.4. The accuracy of the focal length determination via the micro-guide eyepiece is higher than via the Bessel method and has at least the same accuracy as when using a diffraction grating [15].

5.1 Baader Micro-Guide measuring eyepiece scales

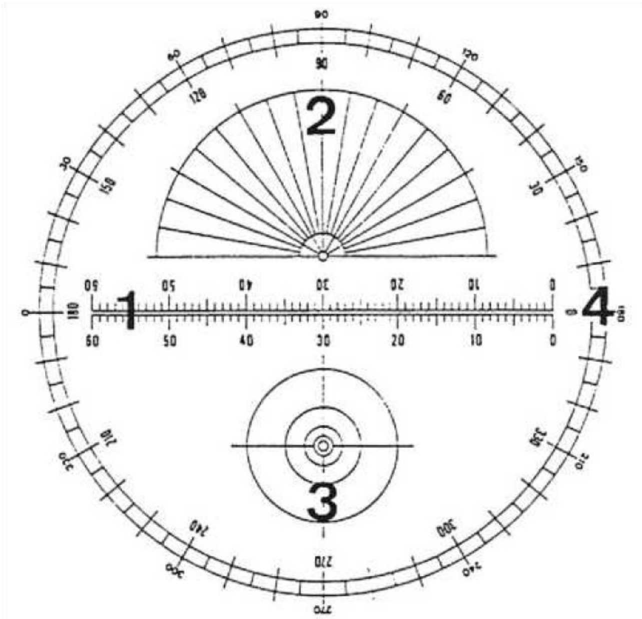


Illustration 7: Baader Micro-Guide
- Image courtesy of © Baader Planetarium GmbH -

(1) Linear scale

- 6 mm long, 60 graduations
- One scale division (ST) = 100 µm
- Distance of the double line = 50 µm (centre – centre). The free distance is ~35 µm

(2) Position angle scale

- Diameter of the centre circle = 100 µm

(3) Concentric circles

- These circles have diameters of:
  - 125, 250, 500, 1000 and 2000 µm

(4) Large angle scale

- The large (inner) scale numbers run in the direction of the position angle when observing with an astronomical telescope,
- The smaller (outer) scale numbers run in the direction of the position angle when a **zenith mirror** is also used

→ Detailed instructions for the Baader Micro-Guide measuring eyepiece are available at [16].

5.2 Baader Micro-Guide measuring eyepiece immage scale

Field of view in arc seconds :

$$\alpha = 15,0411 \cdot t \cdot \cos(\delta)$$

α - Field of view in arc seconds

t - lead time

δ - Declination

Imaging scale scale part :

$$\alpha_{ST} = \frac{20626,5}{f}$$

With 1 ST = 0,1 mm = 100 µm

f - focal length in [mm]

α - arc seconds ["/ST]

Calculating the object size :

$$\alpha = \frac{206265 \cdot D}{E}$$

α - Angle in arc seconds D - Diameter/size in [Km] E - Distance in [Km]

5.3 Image scales for Equinox 120/900 and Williams 80/545

F [mm]	V	ST_1	DL_1	FA_{DL-1}	$Circle_2$	K1	K2	K3	K4	K5
545	44 x	37,8“	18,9“	13,3“	37,8“	47,3“	94,6“	189“ / 3‘9“	378“ / 6‘18“	757“ / 12‘37“
1134 (2x)	91 x	18,2“	9,1“	6,4“	18,2“	22,7“	45,5“	91“ / 1‘31“	182“ / 3‘2“	364“ / 6‘4“
901	71 x	22,9“	11,45“	8,0“	22,9“	28,6“	57,2“	114,5“ / 1‘54,5“	229“ / 3‘49“	458“ / 7‘38“
1864 (2x)	149 x	11,07“	5,53“	3,9“	11,07“	13,8“	27,7“	55,3“	111“ / 1‘51“	221“ / 3‘41“

ST_1 : Scale 1 - One part of the scale
DL_1 : Scale 1 - Distance of the double line (centre - centre)
FA_{DL-1} : Scale 1 - The free distance between the double line
$Circle_2$: Scale 2 - Central Circle
K1 Scale 3 - Inner circle
K2 Scale 3 - Intermediate circle
K3 Scale 3 - Intermediate circle
Scale 3 - Intermediate circle
Scale 3 - Outer circle

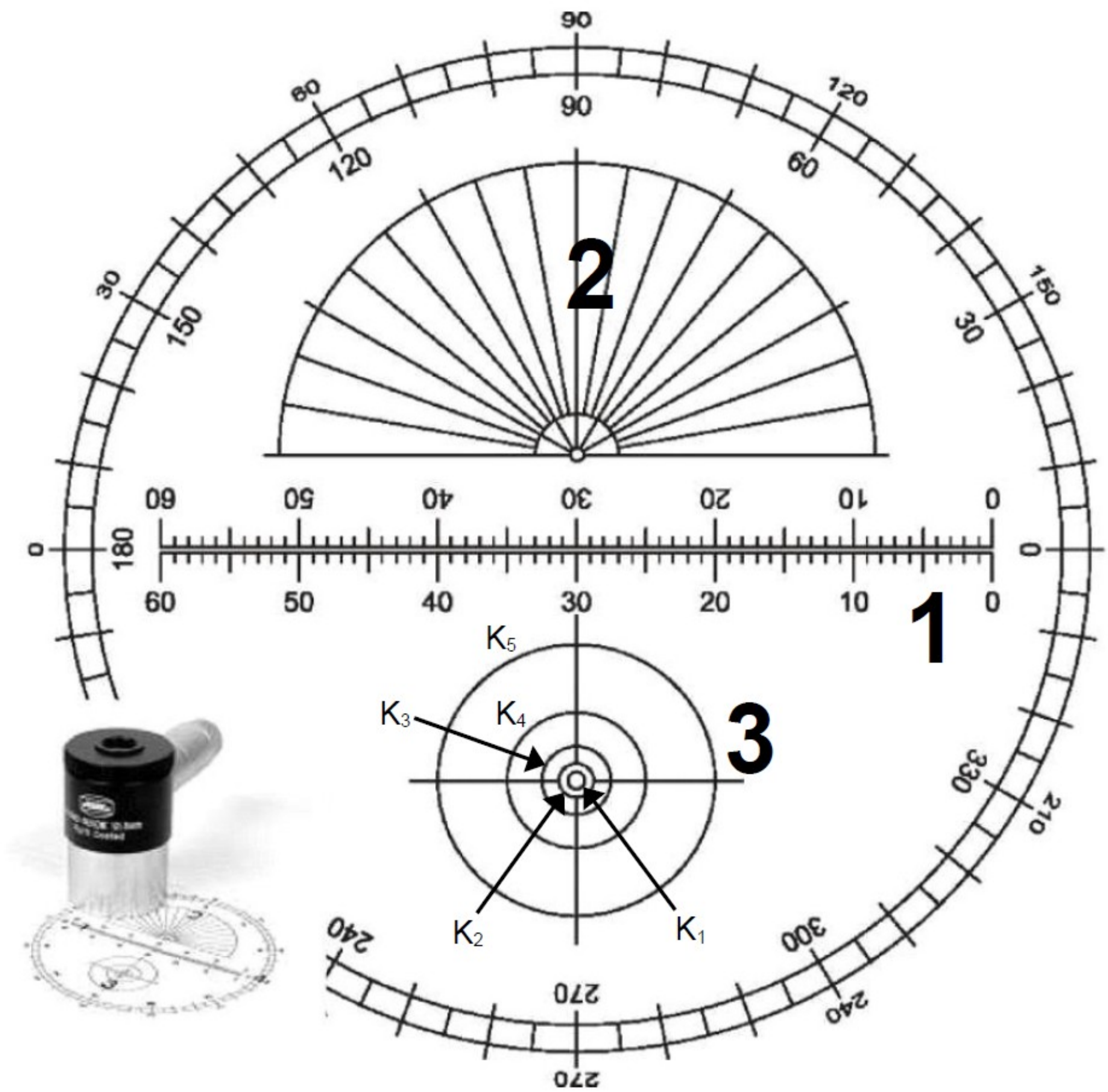


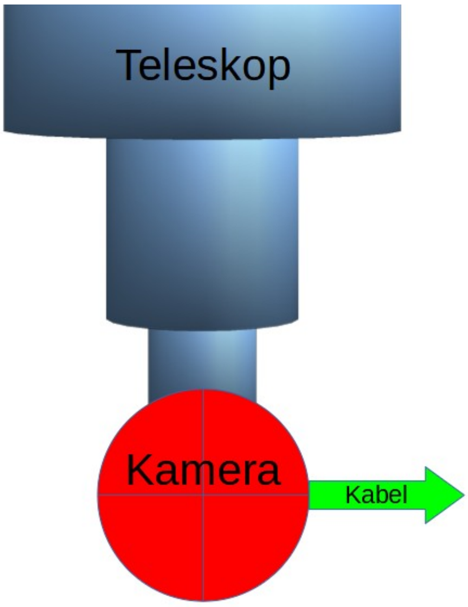
Illustration 8: IBaader Micro-Guide – Image scale
- Image courtesy of © Baader Planetarium GmbH -

6 Calibration of the measuring system

The measuring system consisting of telescope, additional optical components, detector and mount must be calibrated. Various methods are recommended for this in the literature [1]. In addition to the exact determination of the focal length, one variant is calibration using double stars that have already been precisely measured, where it has already been proven that neither the distance nor the position angle change significantly over the years or that the exact distances and position angles are known for different years. This type of calibration using reference double stars is described below.

6.1 Camera alignment & software configuration

Illustration 10: View of the ZWO ASI from



above

The use of an equatorial mount, a suitable camera alignment on the focuser and settings in the imaging software make it easier to analyse the results later. The camera should be aligned in the focuser as shown in the image on the right.

→ With this alignment, the cable is led away at an angle of approximately 90°.

It should be noted that a 90° star diagonal mirror is used to achieve focus even without an extension tube.

This arrangement allows the detector to record true but laterally inverted images.

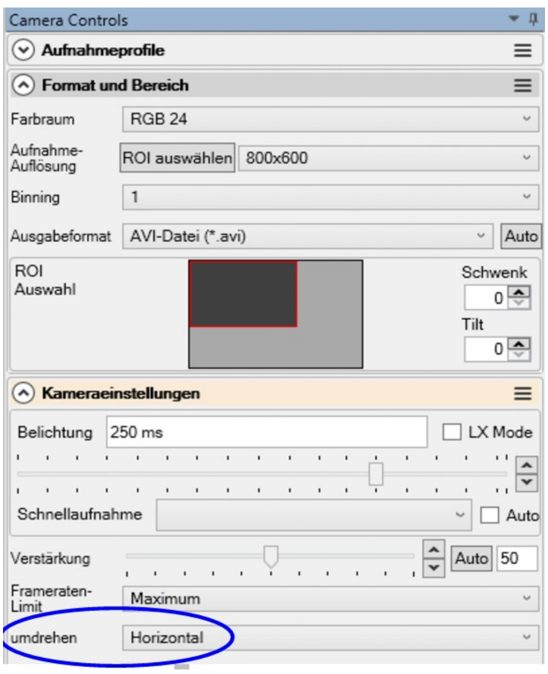


Illustration 11: SharpCap settings

The **SharpCap** software is used for recording.

Settings :

- Colour space RBG 24 (ZWO ASI 120MC-S)
- Resolution 800x600 (volume reduction)
- Binning 1
- Output format AVI/SER
- Exposure dyn.
- Amplification dyn.
- Frame rate limit Maximum

- turn over : Horizontal

To compensate for the laterally inverted display due to the zenith mirror, the configuration parameter *flip* should be set to *horizontal* in SharpCap. This creates a laterally correct and upright image, with the cardinal points always correctly aligned.

6.2 Guidelines for the selection of reference double stars

According to [1 / 15.7.2], the separation of reference double stars should be at least 10 x FWHM, which for the 120/900 Equinox means that the reference double stars should have a minimum separation of 10" (10 * 0.915").
According to [4.3.1], the maximum distance of a double star to be measured may be ~100", when measuring in primary focus and using a Barlow, in order to keep the measurement error below 0.1".

➔ Minimum distance of the reference double star >= 10"

➔ Maximum distance of the double star to be measured <= 100"

Distance to measure double stars	Ideal distance reference double star
< 2"	N/A - Measurement usually not possible
2" .. 25"	10"..20"
26" .. 55"	35" .. 45"
56" .. 100"	75"
> 101"	> 100"

6.3 Calibration using the example of Mizar (STFA 1744)

Observation with the ED-APO 120/900 mm. With a calibrated value for the ***focal length*** of 2703 mm, determined from the measurements using the Baader Microguide eyepiece, the actual distance of 14.48" is determined. The tripling of the physical focal length is due to the 3x superresolution (3x drizzle) used during image processing. The actual focal length of 901.3 mm is derived from this.

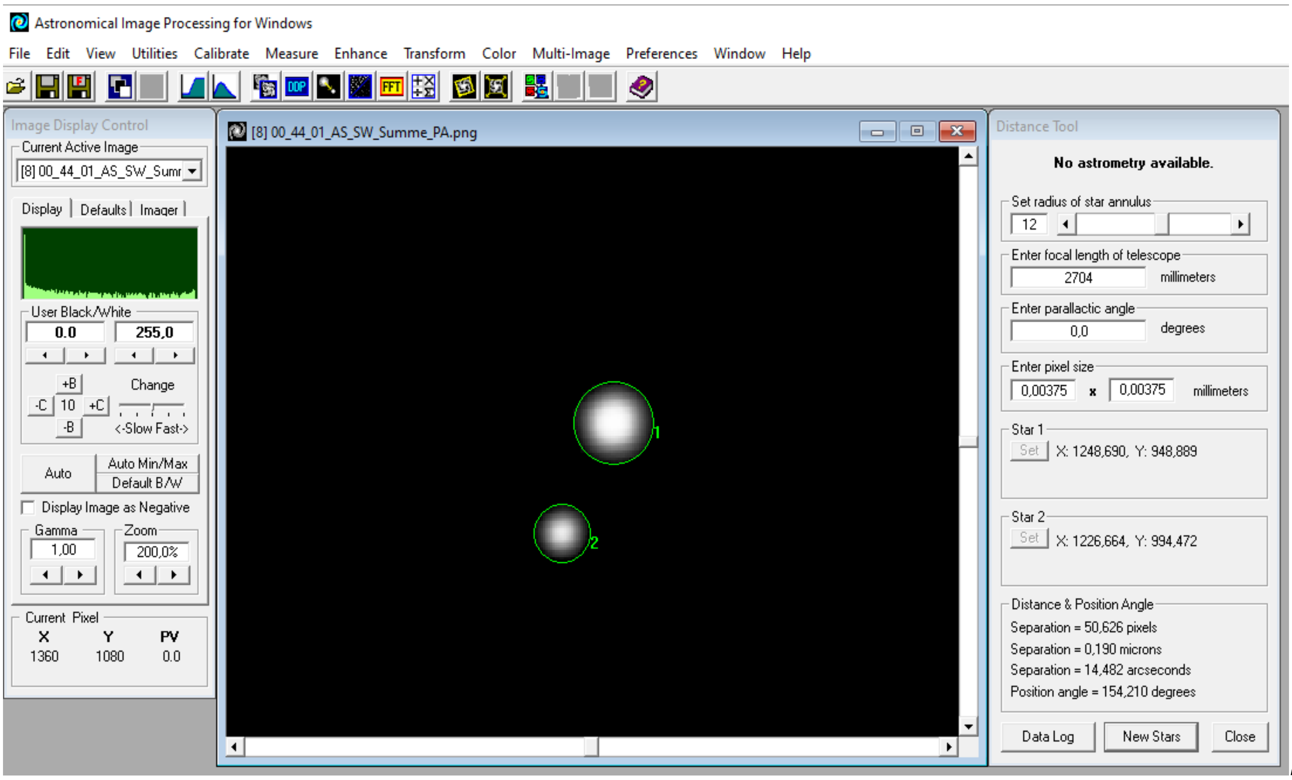


Illustration 12: Calibrated separation, calibrated position angle

The '***parallactic angle***' in AIP4Win (calibration/correction angle) of θ_K is calculated from the difference between the actual PA of Mizar θ_{REF} =153.4° and the by AIP4Win measured PA θ_{AIP}.

$$\theta_K = (\theta_{REF} \pm \theta_{AIP})$$

7 Double star measurements - data reduction

After the creation of SERs/AVIs of double stars, several processing steps follow in order to obtain the actual measurement results. Finally, the results can be published.

7.1 Stacking with AutoStakkert!

The recorded AVIs/SERs should consist of between 100..1000 frames in order to have a sufficient number of frames for the subsequent stacking. Various programmes can be used for stacking. When selecting a programme, it is important that it is also able to stack stars. I regularly use AutoStakkert4 [4] for stacking.

AutoStakkert is also capable of stacking narrower components, although there are limits if the components are too close together, see above.

OPEN SER/AVI

- Select double star

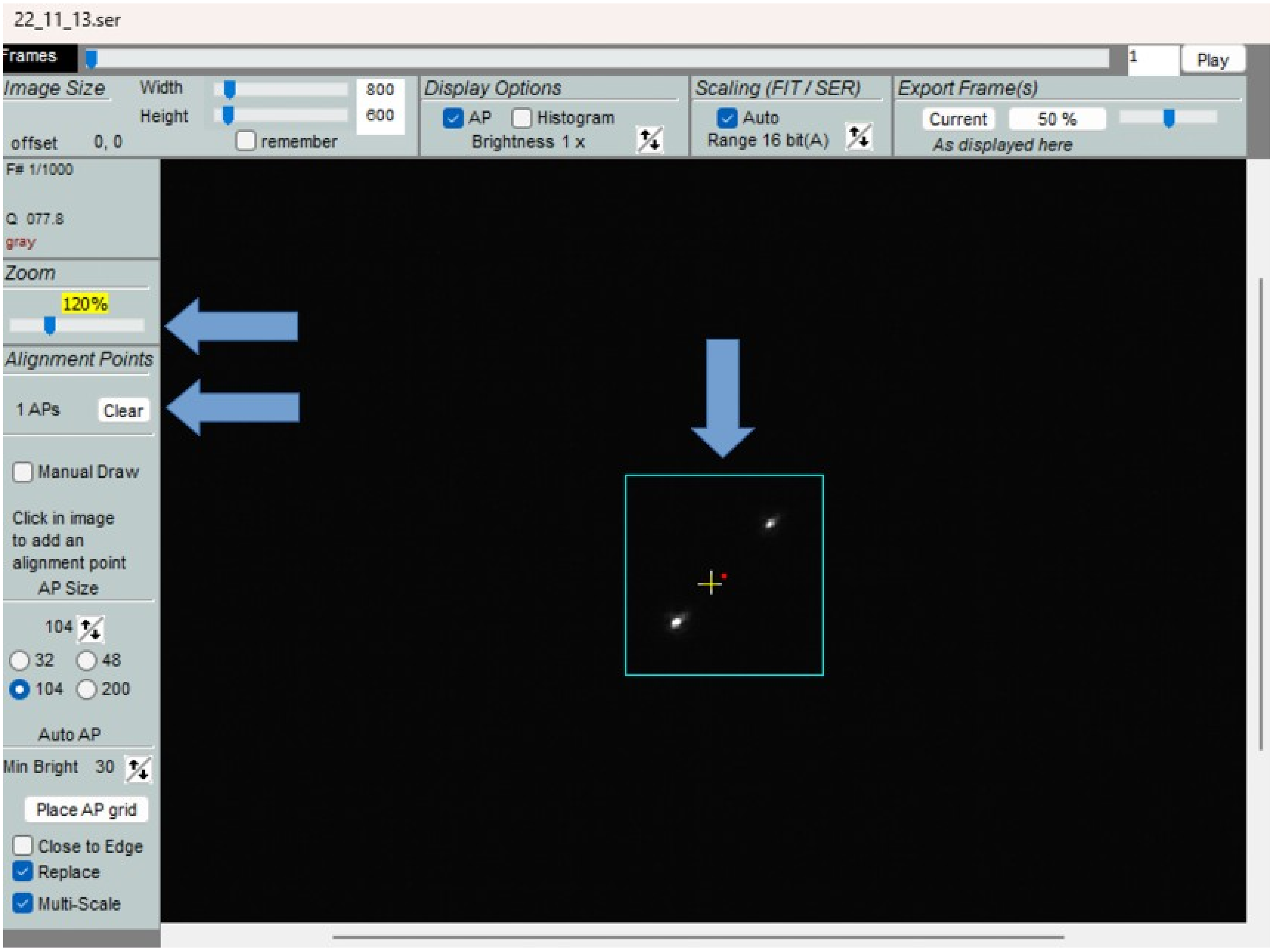


Illustration 13: AutoStakkert! - Configuration (I)

CONFIGURATION:

- Menu → Memory Usage → Adaptive Buffering
- Menu → Colour → Greyscale (ASI678MM) / RGB (ASI120MC)
- Menu → Advanced → Brute Force Alignment

Image stabilisation *Planet (COG)* → centred on the largest and brightest group of pixels

- *Dynamic Background* selected
    - Define an *alignment point* (mouse click on double star)
    - Define the alignment field size in the image as small as possible

Note : *Surface* stabilisation is used for moon and sun

Quality Estimator : *Automatic*

→ *Noise Robust* : 3 (default)

- Higher value for poor seeing or low contrast (noise)
- Lowest value (2) only for undersampled images with a very high SNR ratio

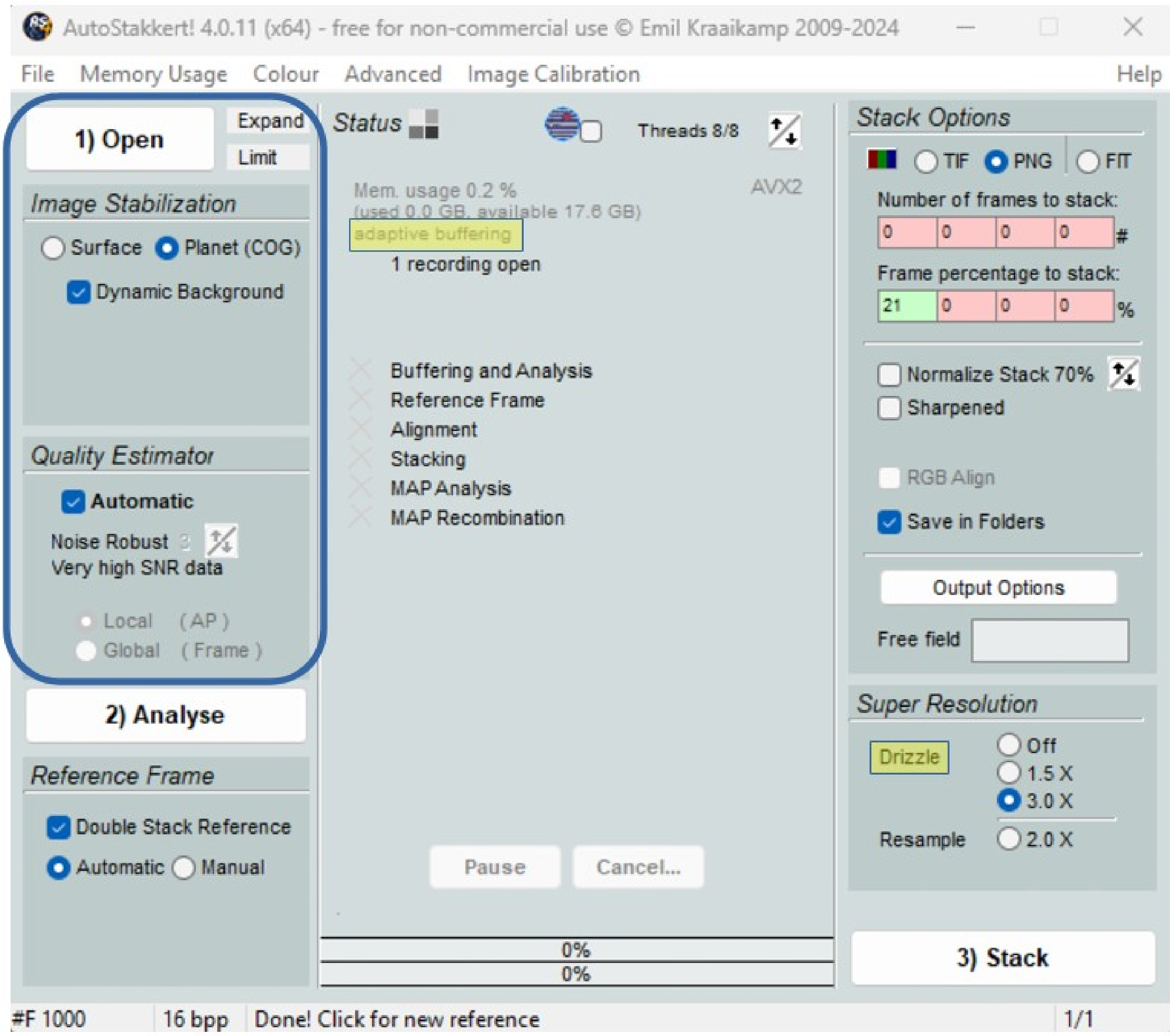


Illustration 14: AutoStakkert! - Konfiguration (II)

ANALYSIS

Pressing **2) Analyse** performs a quality estimation of all frames and creates a **quality graph** in the main window. The quality graph shows the frame quality over time (grey line) and the distribution of the frames sorted by quality (green line), scaled from their best (top left) to their worst (bottom right) values.

The quality graph provides an indication of how many frames should be stacked. Normally, anything below the horizontal quality line of 50% can be ignored when stacking.

By pressing CTRL+right-clicking in the quality graph at the point where the majority of frames are below the 50% line, you can automatically define the corresponding percentage of frames to be stacked. A bold vertical line appears in the quality graph at this position and the selected percentage is displayed in the **stack options**.

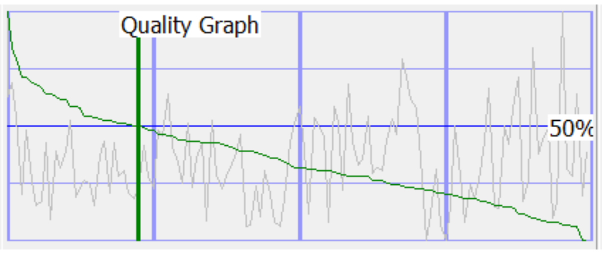
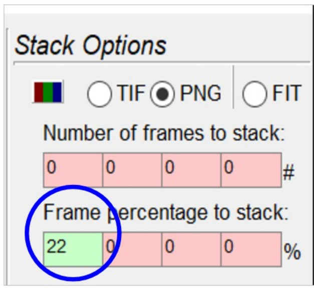
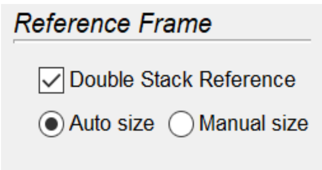


Illustration 15: AutoStakkert! - Quality Graph



Reference Frame :



Double Stack Reference → Double alignment and stacking

Auto size / Manual size → Auto size

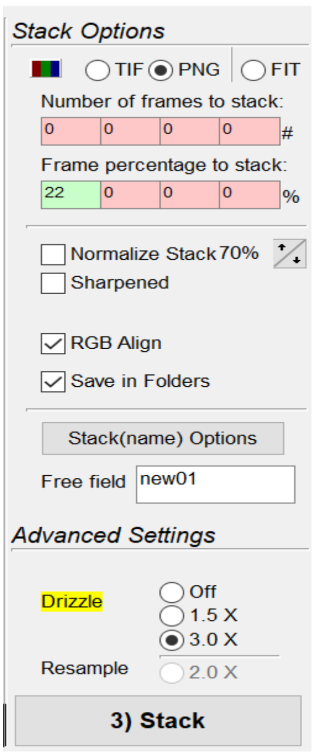


Illustration 16: AutoStakkert! - Stack Options

Stack Options :

Output file format → TIF or PNG

Percentage of frames to be stacked → from Quality Graph

Normalize brightness of resulting *stack* → OFF

Also save *sharpended* pictures → OFF

Align RGB stack on subpixel level → for Color cam only

File name of stacked image

Drizzle : HST technique for undersampled images to improve resolution.
Drizzle = 3.0x

Resample : Enlarges the image via bi-cubic interpolation

7.2 Measuring accuracy - Centroids

At λ=550 nm, the Airy disc of the 120/900 Equinox theoretically has a diameter of 2.306". Using the example of STF730, the FWHM width was measured using AstroImageJ, at an effective focal length = 5700 [mm]

Separation	9.69"	PA : 141°
A: FWHM	16.07 pixel * 0.1357"	**=2.18" (**measured**)**
B: FWHM	**13.92 pixel * 0.1357"**	**=1.89" (**measured**)**

Illustration 17: Measurement accuracy - Centroids (I)

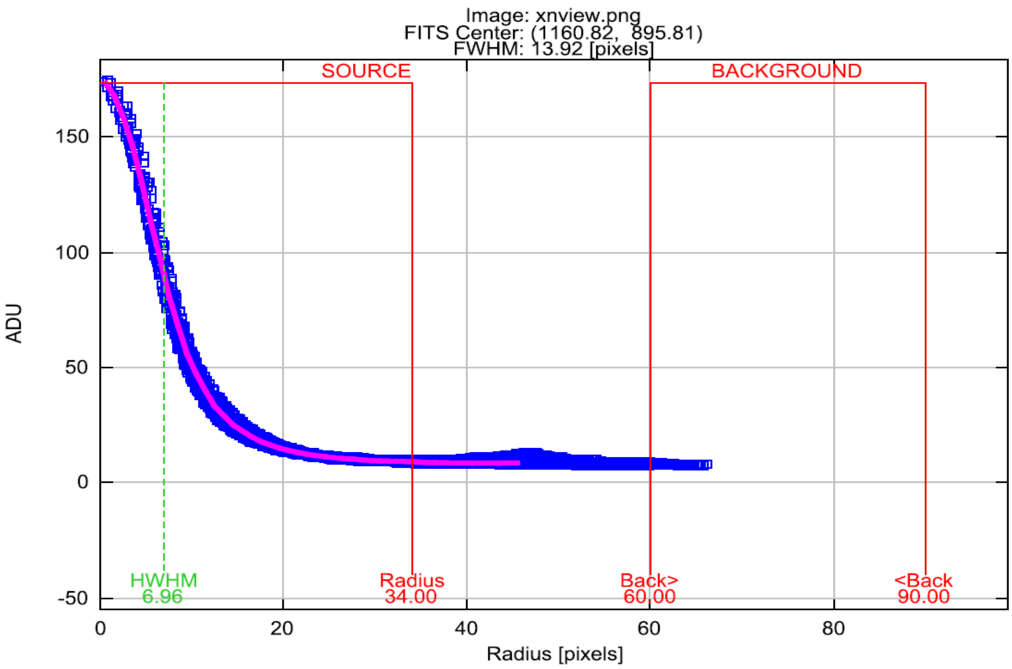


Illustration 18: Measurement accuracy - Centroids (II)

8 Analysing the measurement data

Various programmes are available for the analysis and thus the determination of separation and position angles. I currently use AIP4Win. However, these values can also be determined using PlateSolve2 and Fitswork, but they have to be determined and calculated manually. AIP4Win does this automatically, so I will limit myself here to the description of AIP4Win.

8.1 Analysis using AIP4Win

Analysing via AIP4Win is relatively simple. Open the summary image. Unfortunately, AIP4Win does not seem to understand TIFF, so I am currently still using PNG files. Sufficiently enlarge the opened image (View → Zoom in) and then start the distance tool of AIP4Win via Measure → Distance Tool. The following data must now be entered:

- Focal length — This is the **calibrated** focal length of the telescope used, whereby the 3x superresolution in AutoStakkert triples the focal length of the telescope
- Par.Angle — Calibration angle from the calibration measurement
- Pixel size — 0.00375 for the ZWO ASI 120MC-S or 0.002 for the ZWO ASI 678MM
- Star radius — Must be customised according to the double star for the components

Star 1 can then be selected and then *Star 2.* AIP4Win then automatically calculates the separation and the position angle.

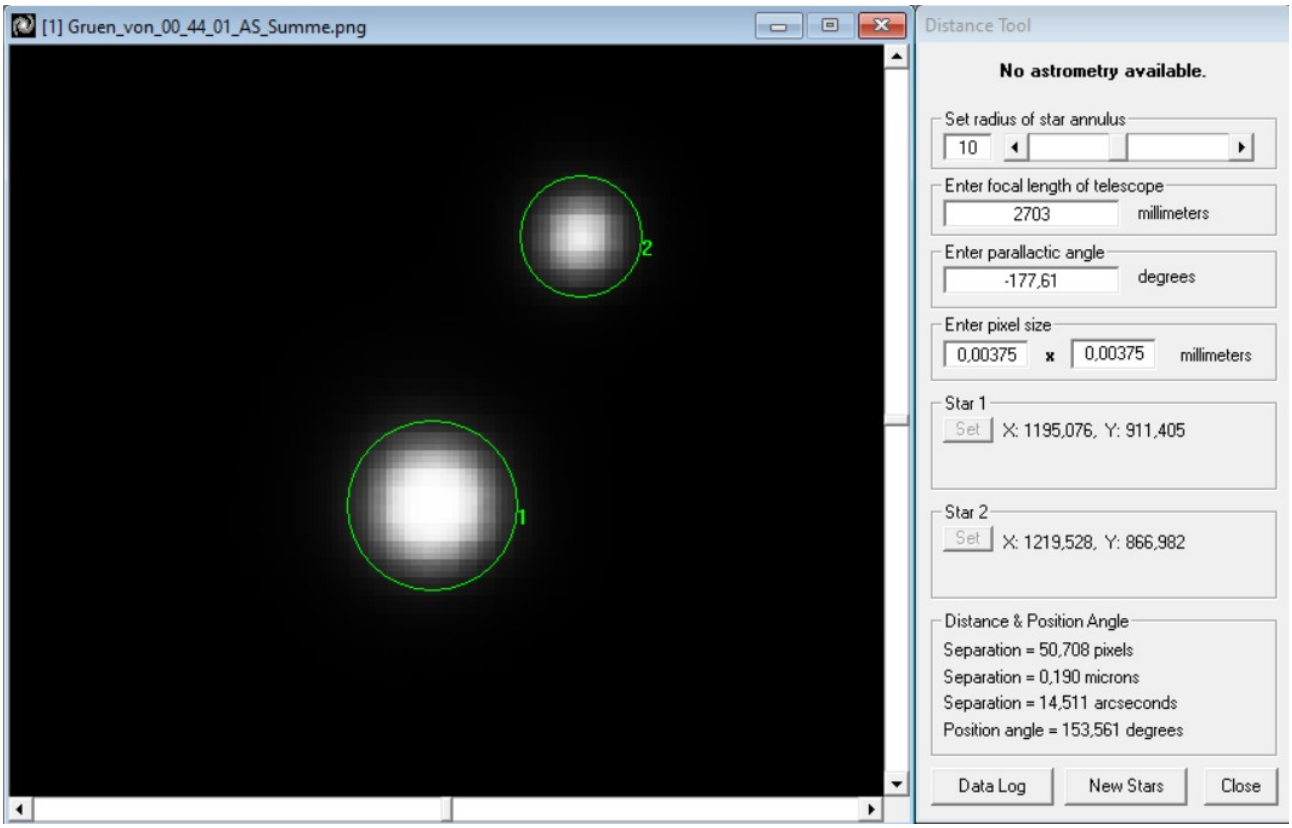


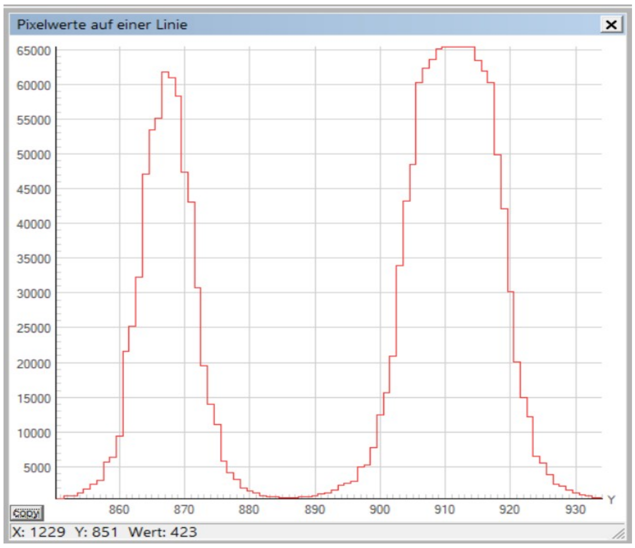
Illustration 19: AIP4Win - Mizar - Calibration

8.2 Analysis using Fitswork

Further interesting analyses can also be carried out with Fitswork, even if the components are so dense that the AIP4Win algorithm stumbles. To do this, the **Display pixel line as diagram** function must be called up in Fitswork under **Edit** → **Other functions**.

A straight line can now be drawn through the centres of the stars and the brightness curve displayed as a diagram. The exact pixel positions of the respective peaks can now be determined via mouse-over and used to determine the distance.

The procedure for calculating the distance is shown in the picture below. It is done simply by applying the Pythagorean theorem (triangular calculation).



Fitswork - Green Channel

A(X/Y) = 1195/912 (X/Y) = 1220/868

ΔX=25 $\Delta P = \sqrt{\Delta X^2 + \Delta Y^2}$ = 50,61 pixel

<u>Δρ = ΔP * 0.2861"/P = 14.48"</u>

8.3 Analysis using AstroImageJ

In the case of very close components or components with a large difference in brightness, it may no longer be possible to determine the distance using AIP4Win. In this case, AstroImageJ opens up a further possibility to at least determine the distance of the components very precisely.

To do this, open the processed image in AstroImageJ. The double star can now be selected using the selection buttons (rectangle, oval). The option **Analyse→Plot seeing profile** is then selected via the menu. The selection can then be adjusted and the seeing profile is plotted.

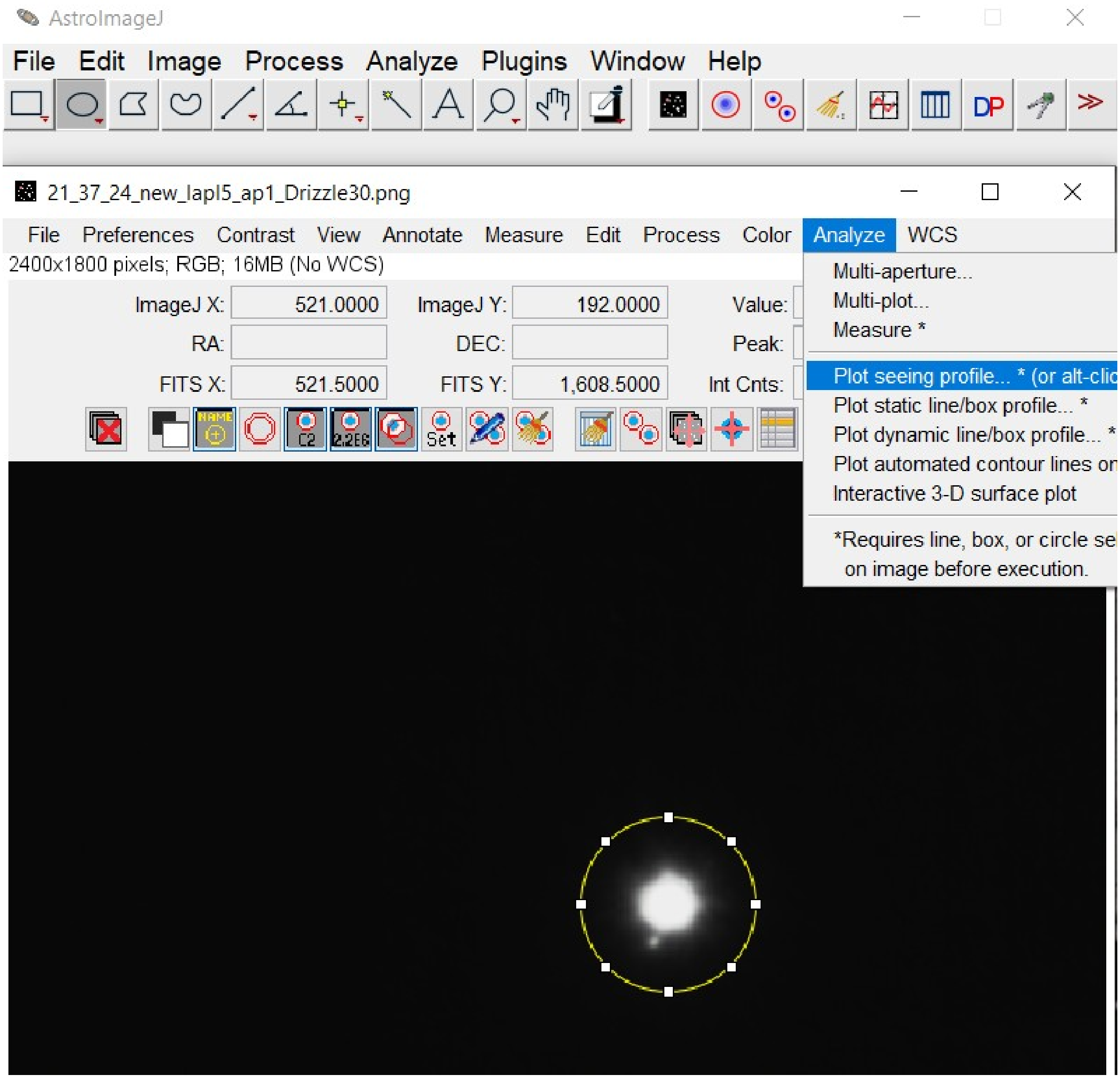


Illustration 20: AstroImageJ - Plot seeing profile

The left edge of the seeing profile is automatically placed by AstroImageJ in the centre of the brighter component and the pixel distance between the brighter component and the second component can now simply be determined using mouse-over, as in the example below.

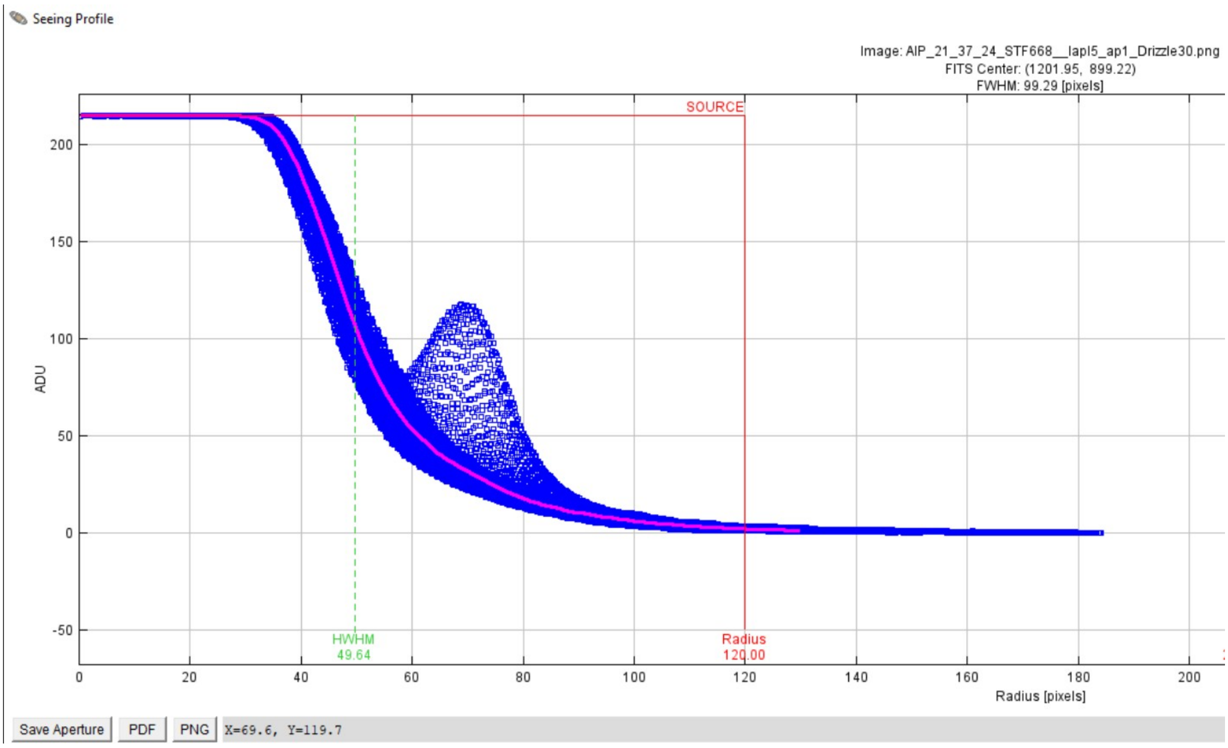


Illustration 21: AstroImageJ - Seeing Profile / Measurement of distance

In the example Rigel, STF668 A/BC ~69.6 pixels, which results in a component distance of 9.46" at an image scale of 0.1359"/pixel.

AstroImageJ also offers other interesting graphical visualisation options. The graphic below also shows the double star Rigel (**Interactive 3D surface plot**):

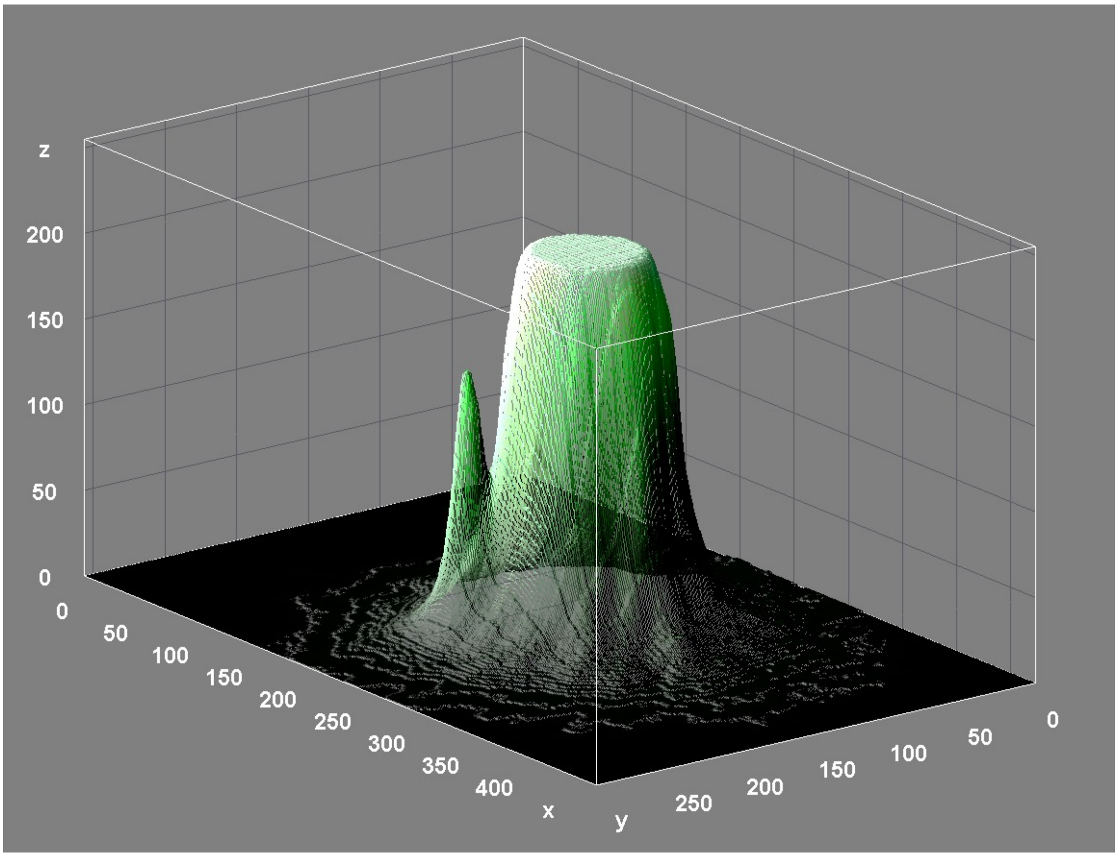


Illustration 22: AstroImageJ - Interactive 3D surface plot

9 Aladin Sky Atlas

The Aladin Sky Atlas allows access to various databases and catalogues and is also freely available for amateur astronomers at [14]. Of particular interest for double star measurements is the Gaia DR3 catalogue, from which the distance and position angle can be determined very precisely for many double stars. Before this is possible, however, Aladin must be configured correctly, see next chapter.

9.1 Aladin configuration on J2016 for Gaia DR3

- Download the Gaia catalogue
- Gaia EDR3 → Properties
  - **Epoch = J2016** **(Attention**: The epoch is reset to J2000 with every restart)

Aladin needs to be configured to Epoch J2016 when using Gaia EDR3 data to achieve the highest astrometric precision. If the default Epoch J2000 is used in Aladin, the software transforms Gaia's J2016.0 data back to J2000.0. This transformation involves Accounting for Proper Motion and Precession Correction:

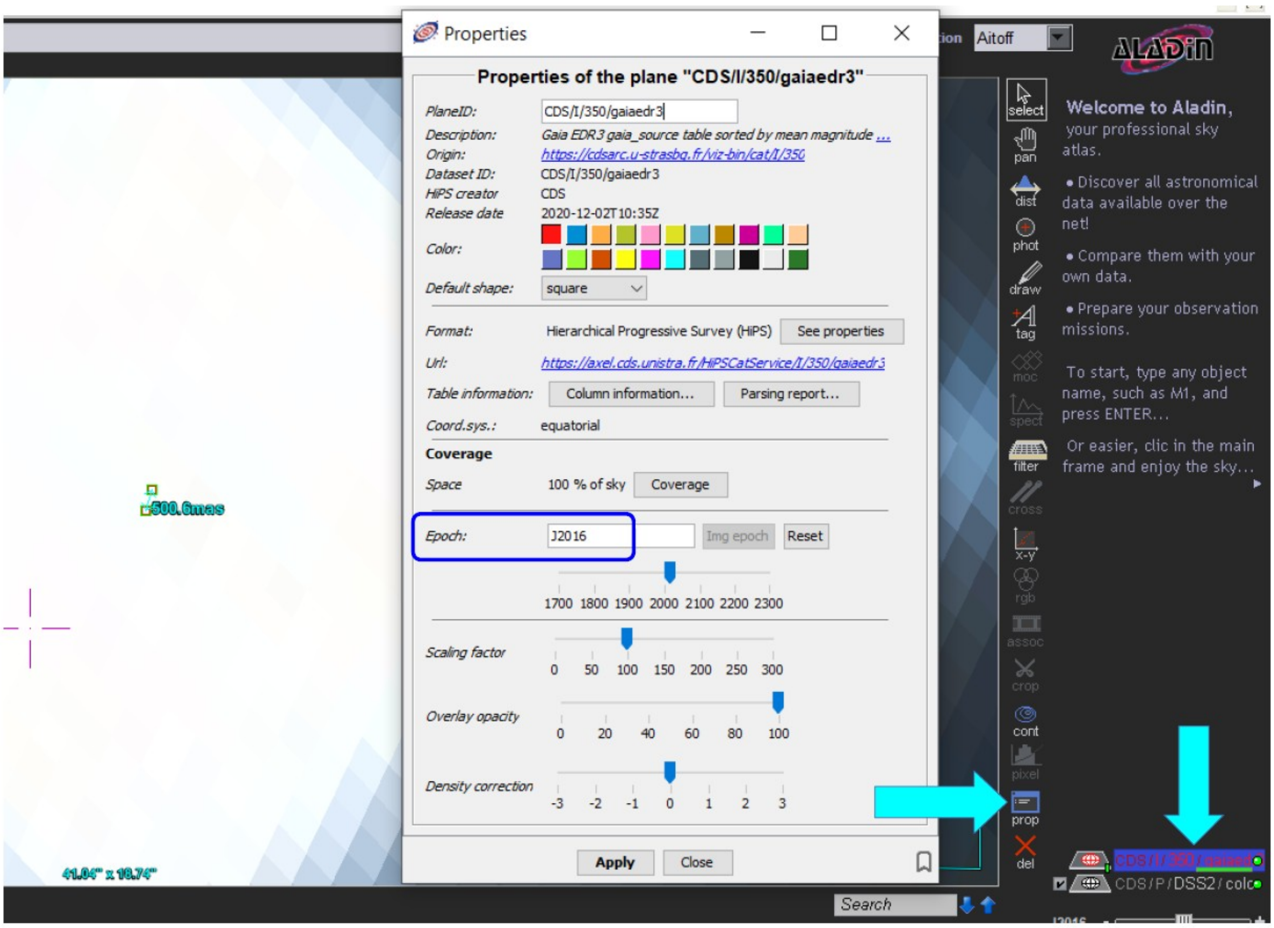
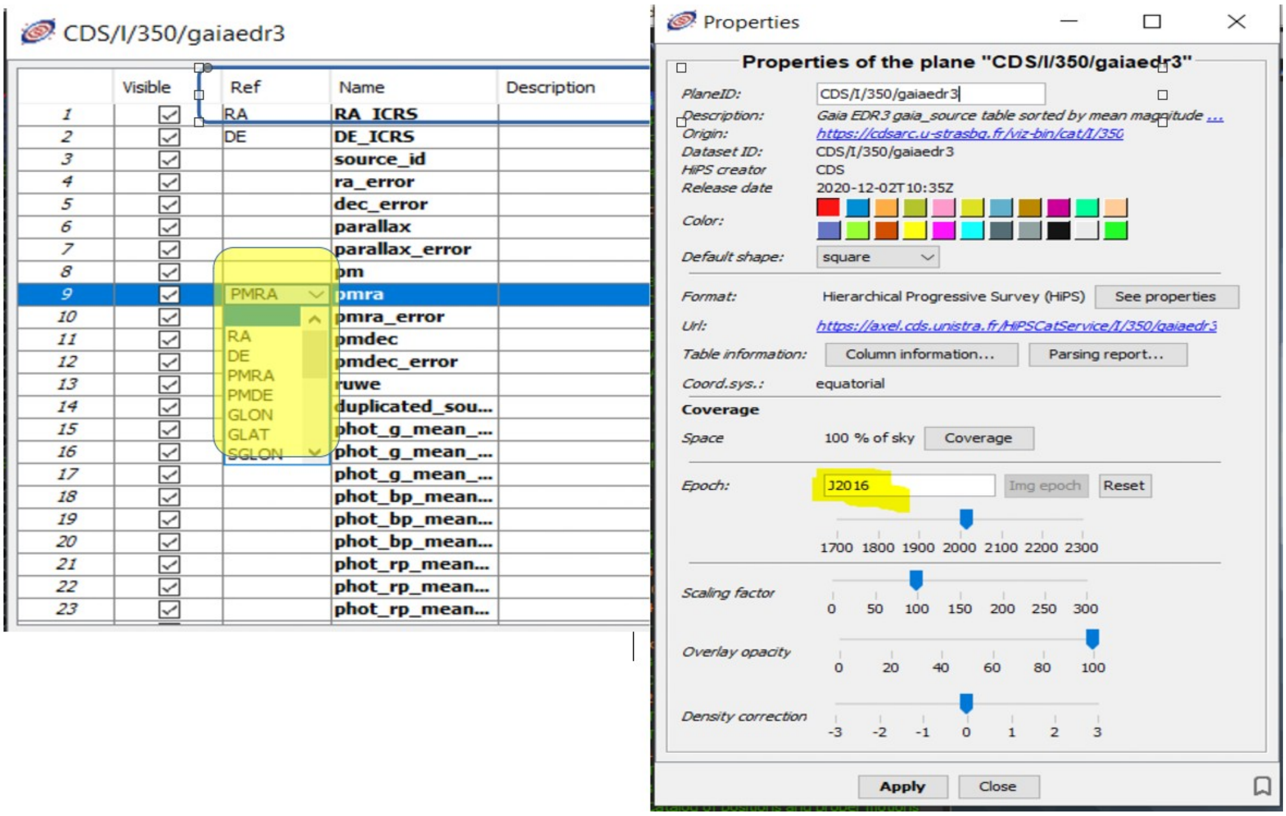


Illustration 23: Aladin - Configuration to J2016 (I)

Illustration 24: Aladin – Configuration on J2016 (II)



9.2 Measurement of a double star in Aladin

Using the example of Mizar, STF1744AB. Unfortunately, Aladin does not recognise the usual designations (STF etc.). Unfortunately, the WDS number cannot be used directly in Aladin because Aladin uses a different syntax. But Aladin accepts the precise coordinates of the WDS catalog, **Coord arcsec 2000** called in www.stelledoppie.it.

WDS 13239+5456 (https://www.stelledoppie.it/index2.php?iddoppia=56796)

Aladin 13:23.9 +54:56

Alternatively, you can also use the following identifiers in Aladin :

- Name of the star if available → Mizar
- Bayer Name → Zeta Ursae Majoris/ Zet UMa
- BD number →BD+55 1598
- Flamsteed number →79 UMa

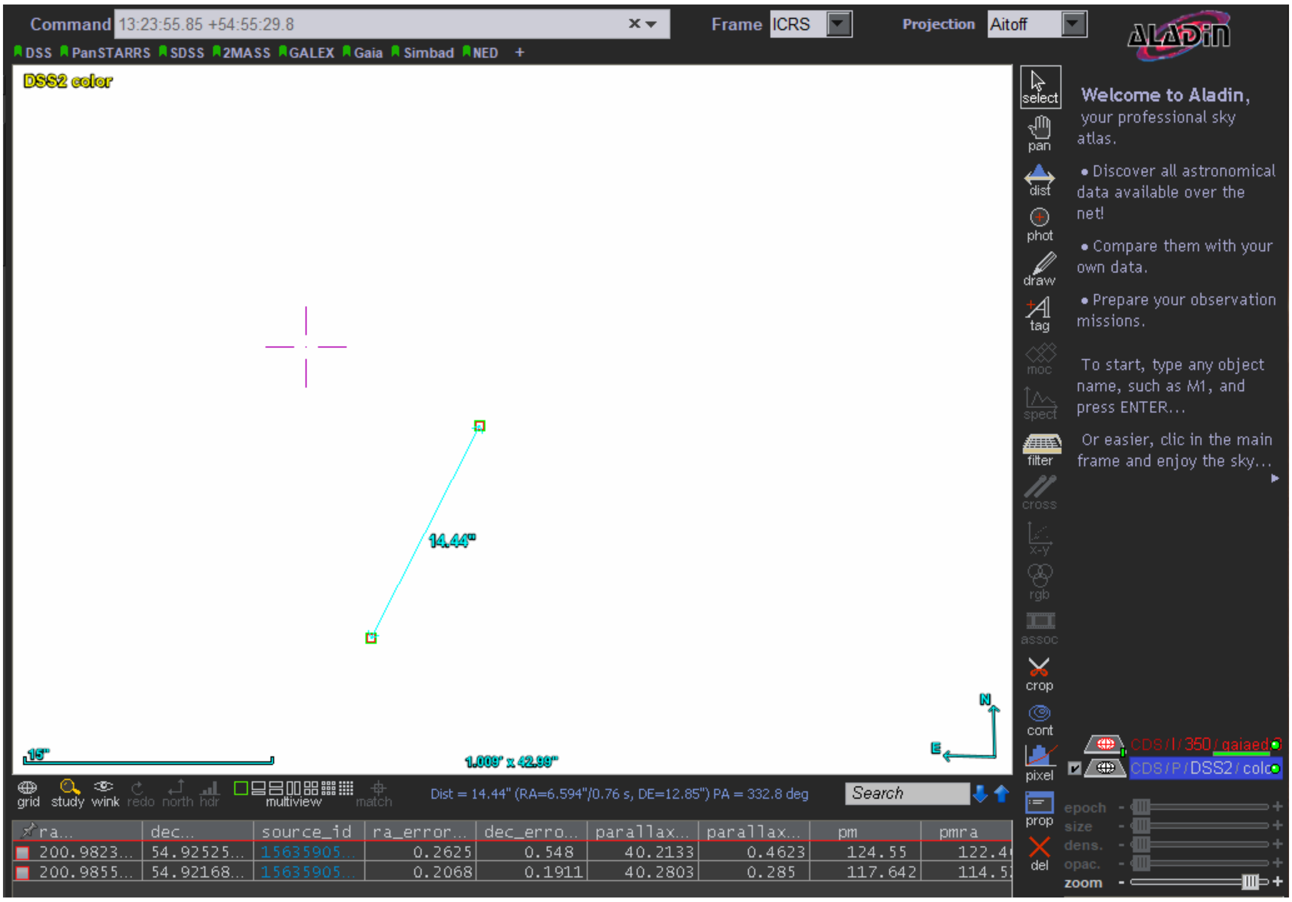


Illustration 25: Aladin – Measurement of Mizar (STF1744AB)

Unfortunately, Aladin calculates the position angle based on the more southerly component, in this case the weaker one. In these cases, 180° must be subtracted from the value calculated in Aladin.

Mizar distance **14.44"**

Position angle 332.8° - 180° **152.8°**

10 AstroImageJ

AstroImageJ is primarily used for processing and analyzing astronomical images, with a strong emphasis on photometry. However, it can also be utilized to measure the separation and position angle of double stars. To perform these measurements, AstroImageJ must first be calibrated with the World Coordinate System (WCS). This calibration requires an account on *nova.astrometry.net*. Using plate-solving techniques, AstroImageJ determines the separation and position angle of double stars.

A detailed description and step-by-step guide can be found in the document *ASTROMETRY AIJ for Double Stars* [18], published by the Boyce Research Initiatives and Education Foundation.

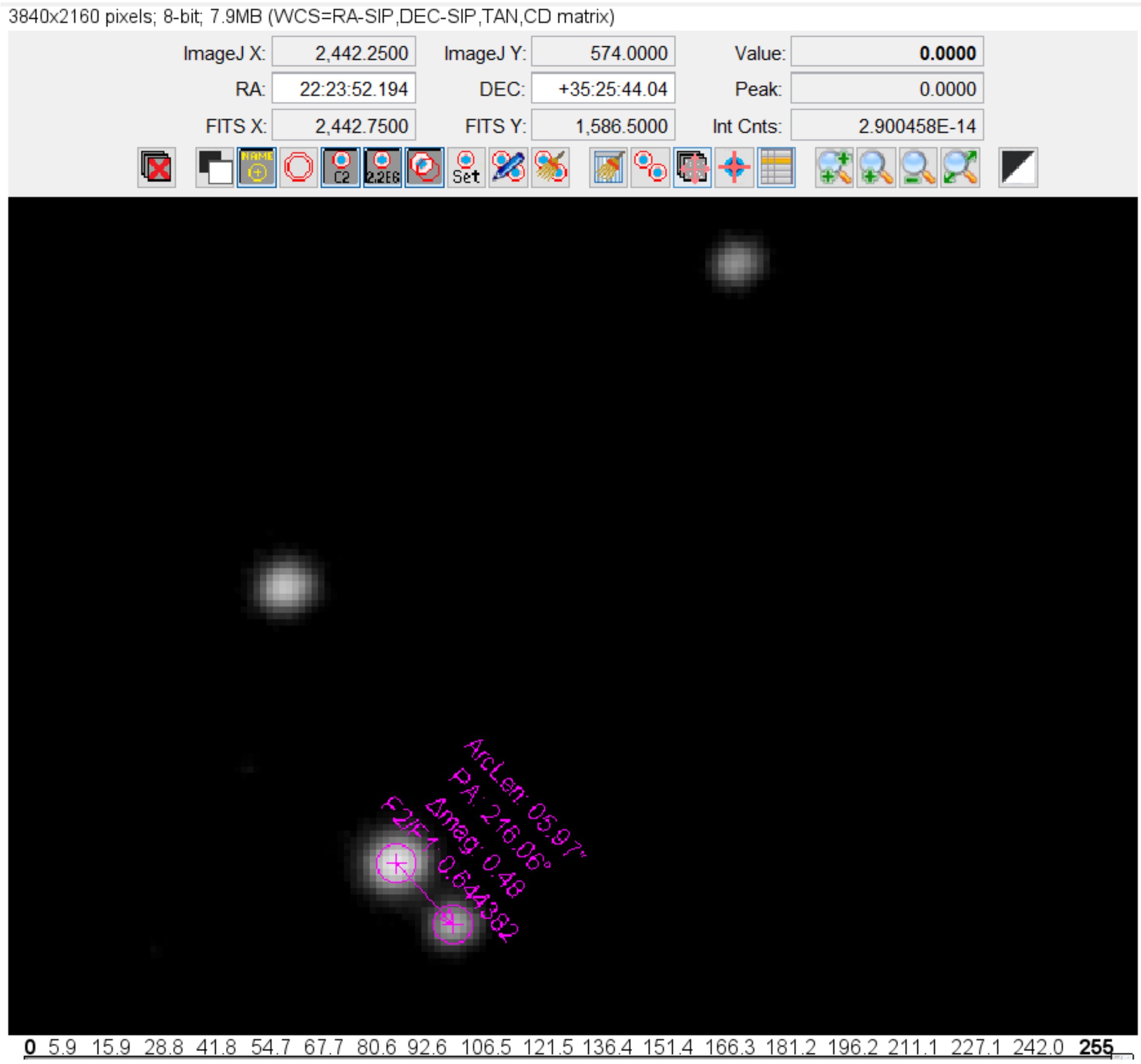


Illustration 26: Measurement of double stars in AIJ

11 List of Illustrations

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13 References

[1] Observing and Measuring Visual Double Stars (Second Edition) - R.W. Argyle (Editor)

[2] Double and Multiple Stars and How to Observe Them - James Mullaney (ISBN 1-85233-751-6)

[4] AutoStakkert! – AS! Stacking Software – Lucky Imaging with an Edge – Emil Kraaikamp – AS!2, AS!3

[5] https://epsilon-lyrae.de/Doppelsterne/Mikrometervergleich/Mikrometervergleich_Leitz_Baader.html

[6] File:Standard deviation diagram micro.svg - Wikimedia Commons

[7] Measuring The Focal Length of a Converging Lens (devinswork.com)

[8] Bessel-Verfahren – Wikipedia

[9] Jenseits des Rayleigh-Kriteriums : das Auflösungsvermögen von Teleskopen
von : Dragesco, Jean / Hägi, Markus

[10] Observation of Large-Delta-Magnitude Close Binaries with Shaped Aperture Masks
Microsoft Word - JDSO online 9-10.docx

[11] Beugungsscheibchen – Wikipedia

[12] REDUC HELP (astrosurf.com)

[13] Bessel Function | Desmos

[14] Aladin Sky Atlas

[15] JDSO - Calibrating the Plate Scale of a 20 cm Telescope with a Multiple-Slit Diffraction Mask

[16] Baader Micro-Guide Messokular - Bedienungsanleitung

[17] Auflösungsvermögen von Objektiven – hwi68 (home.blog)

[18] Microsoft PowerPoint - BRIEF Video Lesson - ASTROMETRY - AIJ for DoubleStars

[19] Refract.exe

14 Annex A

14.1 Links

Double stars
→ www.epsilon-lyrae.de

VdS double star observations
→ Fachgruppe Deep-Sky - Vereinigung der Sternfreunde e.V. (vdsastro.de)

Astronomical Files from Black Oak Observatory
→ Astronomical Files from Black Oak Observatory

Tutorial on the REDUC software by Florent Losse
→ REDUC HELP (astrosurf.com)

Home of AIP4Win
→ AIP4Win@groups.io | Home

Cloudy Nights Forum – Double Star Observing
→ Double Star Observing - Cloudy Nights
→ Getting Started in Double Star Research - Double Star Observing - Cloudy Nights
→ The BEST Triple Stars - Ranked! - Double Star Observing - Cloudy Nights

Journal of Double Star Observations
→ Journal of Double Star Observations
→ JDSO.org (deprecated)

The Webb Deep-Sky Society – Double Stars
→ Webb Deep-Sky Society: Double Star Section (webbdeepsky.com)

The Washington Double Star Catalog
→ The Washington Double Star - Home | USNO (navy.mil)
→ http://www.astro.gsu.edu/wds/ (Mirror)

Stelle Doppie (Front-end to multiple double star and other databases)
→ Stelle Doppie - Double Star Database

VizieR database
→ VizieR (unistra.fr)

Aladin Sky-Atlas
→ https://aladin.cds.unistra.fr/

AstroImageJ
→ AstroImageJ (AIJ) - ImageJ for Astronomy (louisville.edu)

Double Star Calculator
→ www.stella-vega.de

15 Annex B

15.1 Stelledoppie – Creation of double star lists

Create double star observation lists using → stelledoppie.

After opening *stelledoppie*, switch to the **DATABASE** area and call up the **Advanced Search** function.

Filter: Between RA/DE

Example, right ascension between 08:00h and 12:00h and declination between 10°...40° :

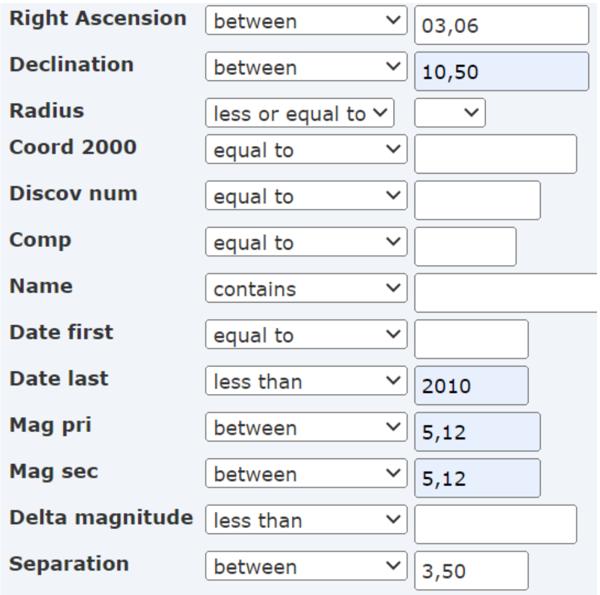

Illustration 27: RA/DE filter in stelledoppie

RA between 03h and 06h
DE between 10° and 50°
-
-
-
-
-
-
All doubles not measured since 2010
Magnitude of primary between 5^m and 12^m
Magnitude of secondary between 5^m and 12^m
-
Separation between 2“ and 50“

The generated list can then be exported e.g. to Excel or saved in the stelledoppie account.

– end of document –