A High Contrast Double Star Filter (HCDSF)

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Abstract

The High Contrast Double Star Filter (HCDSF) was developed for measurements of large delta magnitudes double stars. The bar profile from an over exposed star image will be transformed into a Gaussian profile and separation and angle can be measured with greater accuracy. The filter unit consists of a polarization filter and a small polarization analyzer stripe. Both are rotatable, so the brightness of the primary star can be reduced to the secondary's brightness in a range up to 10 magnitudes. After passing the filter unit both components have the same brightness. That's why the filter offers a much better contrast as solutions which uses constant occultation. Also exposure times are much shorter. An optical relay unit transmits the primary focus which is used as filter plane to a CMOS camera. The filter is mounted in ocular adapter of a 12-inch Newtonian telescope with focus length of 1500 mm.

1. Introduction

Measurements of large magnitudes double stars are always a challenge even if both components are widely separated. The primary star is overexposed and the center cannot be identified with great accuracy. The light curve of such an overexposed star can be easily described as a bar. The goal is to transform this light curve into a Gaussian profile.

In 2007 Daley proposed a method to measure large delta magnitudes doubles with occultation of the primary star with a Baader solar foil stripe. The foil originally made for visual solar observations reduces the brightness of a star about 10 magnitudes. By using the occulter the center of the primary component can be found as a small point in the middle of the stripe. Daley's article was very inspiring and I started first tests in 2017. From the beginning I decided to use a LINOS Microbench system for mounting the optical components. This system consists of mounting plates for the optical components and rods which connect the plates in a flexible and stable way. For the optical relay system two inexpensive CS objectives with 8 mm focus and F1.0 aperture were used. In combination with my CS CMOS camera the optical system was easy to handle. Especially the system could be focused without moving the optics against each other. However, the results were disappointing because of the resulting vignetting on my 12-inch Newtonian telescope. Also the tests with different occultation filters weren't successful. Finally the project was put on hold for 5 years.

In 2022 I started with development of a second version of this filter. The idea was to use only F/5.0 aperture optics for the relay system. This aperture is given by my 12-inch telescope which has a primary focus of 1500 mm. For testing 2 plano-convex lenses without coating were procured. As expected, the optical relay systems shows strong chromatic aberration which could be fixed with a narrow band filter. The disadvantage of this combination was long exposure times, which increased by a factor of 10. The advantage of this relay system was uniform illumination without visible vignetting. Also the star images were of good quality. Only the problem with the occultation filter wasn't fixed. The Baader foil leads to long exposure times, but the filter should work with much shorter exposure times. During some research for material for filter, the idea to use a polarization stripe as filter was born. With this solution in combination with achromatic lenses the concept for the improved version was found. This third version will be described in detail in the next section.

2. The High Contrast Double Star Filter (HCDSF) design

The HCDSF is a less complex instrument which consists of a filter unit with a plano convex field lens, an F-stop and a separate optical relay system to transmit the image plane from primary telescope focus to the CMOS camera (figure 1). Because of the field lens the interaction of the optical elements is very sensitive but important to minimize the optical distortion of the CMOS image. The filter has an overall length of 26 cm including ocular adapter and CMOS camera. The length of the tubes is 16.5 cm. The weight is about 400 g.

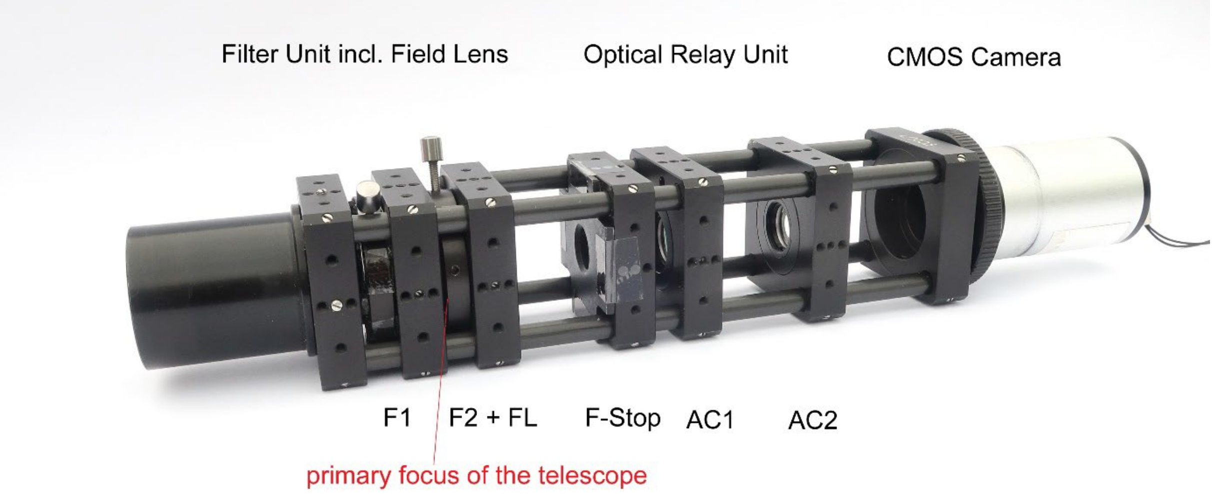

Figure 1 shows the HCDSF instrument. Mounting plates contain the optical elements and are connected with 4 tubes. On the filter unit there are only 3 tubes so the polarization filters can be rotated in wider range

2.1 Mircobench system

The HCDSF instrument is based on the LINOS Microbench system, but components from other manufacturers and some self-made spare parts are used too. The Mircobench systen was developed by the QiOptiq predecessor Spindler & Hoyer in 1963 and can be found in optical laboratories in various versions or in combination with other systems. The original system consists of aluminum mounting plates which are connected with 4 steel rods. Therefor a mounting plate has four 6 mm holes in the corners. In the center of the mounting plate is a hole with diameter of 25, 30 or 35 mm to pick up the optical elements. For testing and calibration the plates can be moved along the rods. To fix the plates and optical elements different kinds of screws can be used. By using thumbscrews no screwdriver is needed. This works well for first tests on telescope at night (figure 2). Different positions of the elements can be easily tested. If the positions of the plates are found the thumbscrews can be replaced later with threaded pins to get more stability.

To protect the optical elements the spaces between the plates are covered with black cardboard. In the current filter version the cardboard is covered with aluminum foil on the outside. This also prevents fogging of the optics.

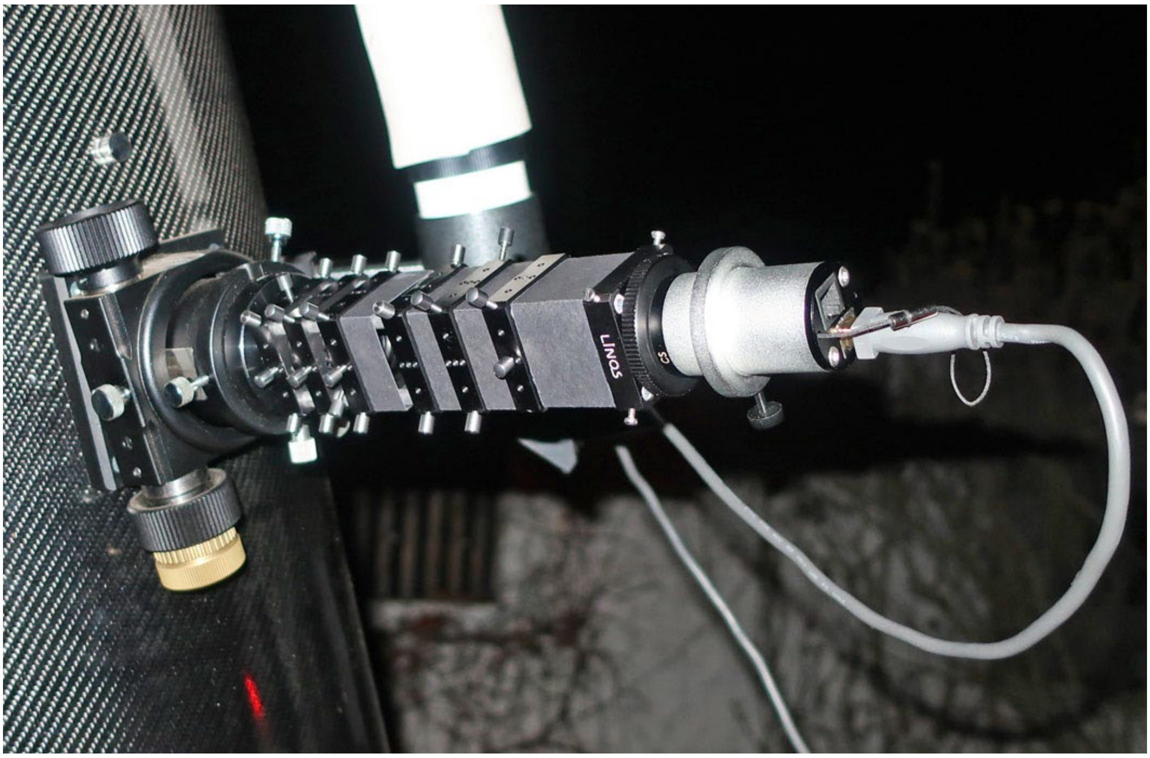

Figure 2 shows the HCDSF instrument first time on telescope in December 2022. In this version tubes of aluminum were used. Mounting plates are still fixed with thumbscrews

For the HCDSF in figure 2 aluminum tubes were used first instead of original steel rods. Aluminum tubes can be easily edited and have less weight than steel rods. In later version the aluminum tubes were replaced by carbon fiber reinforced plastic. This material offers strength and rigidity, low weight and an extremely low thermal expansion. For temperature differences of 10 K the linear expansion of the filter is only 0.3 µm. Calibration of the filter by a moderate ambient temperature range the focus should be the same in summer and in wintertime. Carbon fiber reinforced plastic can also be easily machined.

Similar opto-mechanics systems like the LINOS Microbench system will be offered by Newport Photonics, Edmund Optics and other companies too.

2.2 Filter Unit

The main part of the High Contrast Double Star Filter (HCDSF) is the filter unit which consists of a linear polarization filter F1 and a linear polarization strip F2 as analyzer (figure 1). The analyzer F2 is located in the primary focus of the 12-inch Newtonian telescope. For better handling the polarization filters one of the four tubes is shorter and only connects the part from F2 mounting plate to the camera mounting plate. Otherwise the thumbscrew which serves as a handle for the filter would be terminated by the tube. With only 3 tubes the rigidity of the Microbench system is a little bit reduced but there is no effect in practice. Therefor both filters F1 and F2 are around 168° rotatable. In this way the brightness of the star placed in the analyzer can be easily adjusted. Stars outside the analyzer will not be changed in their brightness. Through that the brightness of the primary component of a large delta magnitude double star can be reduced to the brightness of the secondary component. With the HCDSF instrument the bar profile of an over exposed star will be transformed into a Gaussian profile. The intensity profile of the secondary component shows no change after adjustment of the primary (figure 3).

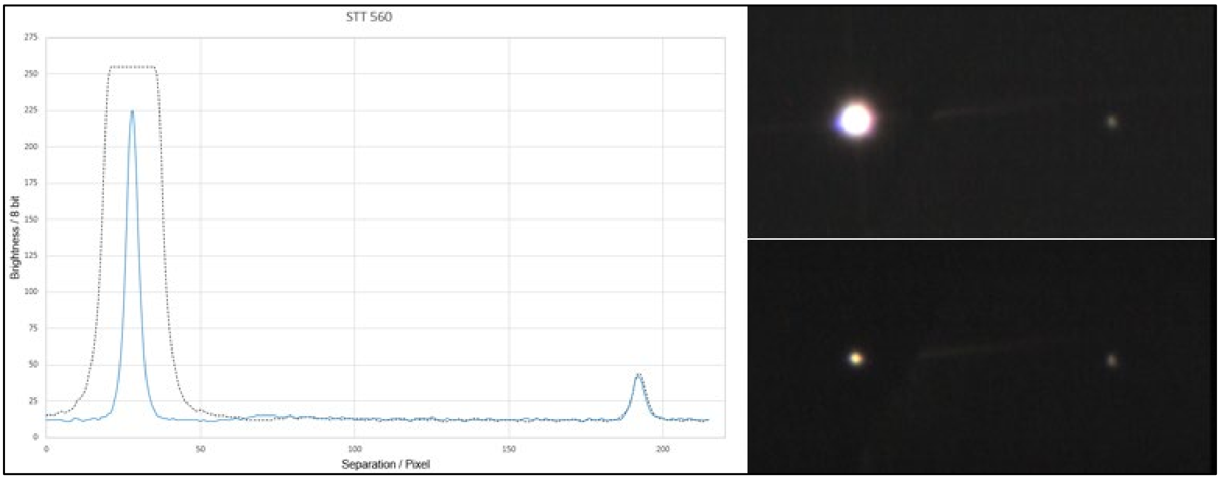

Figure 3 shows the intensity profiles and the images for the unfiltered (dotted line) and the filtered image (blue line) of STT 560. Brightness of the primary is 3.22 magnitudes, the secondary has a brightness of 11.31 magnitudes. Δm is 8.09 magnitudes. Exposure time was 1 s

The filter unit itself is located in front of any further optical elements. Polarization filters pass~~es~~ the light in the direction of the polarization plane and reflects all other parts. That means that the most light of the adjusted primary star will be reflected by the analyzer F2. The polarization filter F1 passes through this reflected light because it's still in plane with the polarization direction. Finally the primary's light will be reflected back to the telescope. This effect is stronger the greater the difference in brightness between the two components. The final contrast of the CMOS image depends on the reduced brightness of the primary.

For both filters F1 and F2 a polarization foil was purchased. This foil is a no name product and is offered for physical experiments of polarized light. The optical quality isn't known. The thickness is 0.175 mm which has a~~n~~ small effect on the image quality and image scale. Because of light refraction by F2 the focus plane of the primary is a little bit different from the secondary component which doesn't pass F2. This difference also influences the measurements of double stars. In section 3.2 the quantitative impact will be discussed. The foils are taped on adapter 30/25 which reduces 30 mm apertures to 25 mm.

However, the real challenge of the filter unit is the manufacture of the analyzer. The dimensions of the analyzer F2 are about 25 mm x 0.5 mm. It will be punched out with a cutting knife. Due to the punch process the edges become opaque, so the primary star can't be located near the edge. Therefor the minimum distance between both components is about 10 arc seconds.

2.3 Field Lens and F-Stop

In the back of the analyzer F2 a plan convex field lens FL is placed in same adapter. The lens has an aperture of 18 mm and a focus length of 30 mm. The lens is mounted and can be directly inserted in the adapter. The distance between analyzer stripe F2 and field lens is 1 mm.

In the original design of Lyot's coronagraph the field lens had the function to focus the telescope entrance pupil on a F-stop to improve the contrast. In section 2.2 it was shown that the most part of the primary's light will be reflected and illuminates the telescope. The field lens can be used to improve the contrast of the camera image too. But the field lens offers more opportunities as only to improve the contrast.

For calculation the interaction between primary focus, field lens and optical relay system the Winlens Basic Software from LINOS was used. Winlens Basic is a free optical design software. The optical elements of LINOS/QiOptiq are included in the database and can be simply selected by their part number. By moving the elements the different spot diagrams, field aberrations, and chromatic aberrations can be calculated. Without a optical ray trace program the interaction of the optical elements can't be understood in detail.

The distance between primary focus plane in F2 and field lens FL has a big influence on the distance between the two achromatic lenses AC1/AC2 to each other to get finally a minimal distortion. The distances must be calculated with an accuracy of 0.1 mm. It is no problem to achieve this accuracy in the Microbench system with help of a caliper. With using a field lens the distance between both achromatic lenses is closer as larger the distance between focal plane and field lens is chosen. That's why the placing of the field lens affects the overall size of the filter. As Daley in his Article already mentioned the field lens is important to minimize the distortion and reduces the Petzval radius too. The disadvantage of the field lens is the increased spot diameter. Also, the field lens is located in the same adapter as the analyzer F2 and will be rotated by using the analyzer. The F-stop is located in the back focus of the field lens. The F-stop element consists of a polyamide plate and was colored. It is fixed with a tape on a mounting plate.

2.4. Optical Relay Unit

The optical relay unit AC1 and AC2 transmit the image plane from the primary telescope focus F2 to the CMOS camera. Therefore two 60 mm f/5 achromatic lenses from QiOptiq were purchased. The lenses are designed for the LINOS Nanobench system and can be used in the Microbench system with adapter. The achromatic lenses have a broadband anti-reflection coating. The focus length is the reason for the overall length of the HCDSF instrument. Therefor the Newton telescope must be adjusted very well. The magnification of the optical relay unit is 1.15.

2.5 CMOS Camera

For double star observations a QHY 5-II color CMOS camera will be used. With C-mount / Microbench adapter the camera can be easy integrated. The CMOS ship has dimensions of 4.83 mm x 3.63 mm but for videos only 2.55 mm x 1.80 mm will be used. The diagonal of the image is 3.16 mm. Pixel size is only 3.75 µm. The transmission of a polarization filter for unpolarized light is only about 30-40%. Also the magnification of the optical relay unit consumes light. The exposure times by using the HCDSF instrument increases on factor 4. However, in practice exposure times range from 1/8 s to 2s are suitable for most cases.

2.6 Assembling the HCDSF instrument

The filter is assembled from the camera side. First the CMOS camera and the achromatic objective AC2 are mounted. AC2 will be moved to focus a distant object (infinity) on the camera. Then the first achromatic objective AC1 will be fixed in the distance to AC2 which was calculated in Winlens software. In third step the plate with F-stop will be mounted near to AC1. Next step is to place the plate with analyzer F2 including field lens FL in focus of AC1. F1 and ocular adapter can be mounted independently. At least the F-stop will be placed on the back focus of the field lens.

3. Calibration the HCDSF instrument

3.1 Regression function calculations for calibration

STFA 7 is a common proper motion pair with nearly constant distance over entire observation time from 1836 to today. Also both components are more or less of the same brightness. With the observation data from the WDS catalog a regression function will be calculated. From this function the separation value for observation date can be taken as reference. To get a suitable regression function statistical outlier of the historical value has to be eliminated.

As a second reference 41 Ari was used (figure 7). In the case of 41 Ari AB, 41 Ari AC and 41 Ari AD comparison the calculated data with measured separations leads to inconsistent results for calibration. This is not as expected because the distances of AB and AC are on the same scale as STFA 7 above. 41 Ari AD in more distance on the opposite leads to same image scale as STFA 7. The contrast of AD isn't so high as AB and AC.

γ Ari (STF 180) is also a well-known double star with a separation of about 7.2''. With observation data from WDS catalog a regression function will be calculated and compared with measurements with the HCDSF instrument. The image scale is more less similar to 41 Ari AB and 41 Ari AC.

Also a good calibration candidate for longer separation values is the high proper motion star δ Leo (Zosma). Comparison the calculated data with measurements leads to more less same image scale as STFA 7 and 41 Ari AD.

The calibration results are shown in table 4. To get an better understanding of the inconsistency of the results it's good to know about the image scale in primary focus without HCDSF instrument. Results of some recent and past calibrations for primary focus of the 12-inch Newtonian telescope are shown in table 5. Calibration stars in both tables are sorted by separation of the components.

Table 4 shows the calibration stars, the calculated regression functions, separation and the resulting image scale for the HCDSF instrument, sorted by separation

Calibration star	WDS number	Regression function	Separation	Image scale
γ Ari	01535+1918	s = -0.0092t + 25.837	7.22	0.441
41 Ari AC	02500+2716	s = -0.0446t + 117.35	27.11	0.438
41 Ari AB	02500+2716	s = 0.0947t – 157.13	27.12	0.440
STFA 7	03311+2744	s = 0.000032t + 44.02	44.08	0.446
41 Ari AD	02500+2716	s = -0.0309t + 184.28	121.77	0.445
δ Leo	11141+2031	s = 0.1583t – 113.3	206.99	0.444

Table 5 shows recent and past calibration stars for the 12-inch Newtonian telescope without HCDSF instrument, sorted by separation

Calibration star	WDS number	Regression function	Separation	Image scale
Castor	07346+3153	Orbit calc. (Doc1985c)	5.45	0.517
Theta 1 Ori AC	05353-0522	s = -0.0008t + 14.465	12.85	0.516
Theta 1 Ori AD	05353-0522	s = 0.001t + 19.453	21.47	0.512
STFA 7	03311+2744	s = 0.000032t + 44.02	44.08	0.513
δ Leo	11141+2031	s = 0.1583t – 113.3	206.99	0.512

By using the HCDSF instrument the image scale increase with separation (table 4), in opposite to calibrations in primary focus which shows a decrease of the image scale with separation. Reason could be that for calculation the HCDSF instrument in Winlens software an achromatic objective was used for simulation the telescope objective. With this optical setup the distortion was a little bit overcompensated for the Newtonian telescope.

3.2 Calibration tests within different sections of the image plane

The results from section 3.1 should be analyzed in more detail. Therefor the image plane was divided into 9 equal parts (see figure 6). STFA 7 was also taken for measurements in each section. Same measurements were also done without the HCDSF instrument. After analyzing the measurements a standard deviation for both cases was calculated: Result for separation with HCDSF instrument is 98.82 ± 0.17 pixel, without HCDSF separation is 85.89 ± 0.10 pixel (note the different image scales!). By using a Baader *Fringe Killer Filter* which cuts both ends of the visible spectrum it was found that in both cases the standard deviation decreases. By using the HCDSF instrument a small effect of the cameras C-Mount could also be detected.

Figure 6: shows a summary of stacked frames f STFA 7 in each of the 9 different sections to analyze local differences of the image scale

In section 2.2 it was already mentioned that the analyzer F2 affects the image scale because of the thickness of the foil stripe. In different tests with STFA 7 it could be found that the contribution is in a range of about 0.05 to 0.2 pixel. With an image scale of 0.446''/pixel the error for STFA 7 is finally less than 0.1''.

All in all can be found that the HCDSF instrument works well for wider pairs in range from 44'' to 207'' with a constant image scale of 0.445''/pixel. For closer pairs a image scale of 0.440''/pixel is more suitable. Every design change (e.g. distance between both achromatic objectives) of the HCDSF instruments requires new calibration.

4. Double star observations with HCDSF instrument

The usage of the HCDSF instrument is very easy but before the start the telescope collimation has to be checked and if needed corrected first. Also the focus plane of the HCDSF instrument is more outside than by typical oculars. Therefor it is good to extend the ocular adapter for visual observations first. If the double star of interest is found and set in the middle of the field of view, the ocular will be replaced by the HCDSF instrument. The instrument must be aligned to east-west direction first. Regarding the position angle the primary star has to be placed in F2. Therefore the analyzer F2 is rotatable so a good position can be found. In cases of wider double stars this position will not be in the middle of the image. After position is fixed the contrast between the primary and the secondary component can be adjusted by rotation the polarization filter F1.

For measurements a video sequence with 50 to 200 frames will be recorded. The number of recorded frames depends on the exposure time. Records will be made with Sharpcap software. For analysis the program REDUC will be used. REDUC identifies the brightest star as primary automatically. Due to this automatism it is better if the primary's brightness in F2 is still a little bit higher than the other components to avoid any later phase shift. Figure 7 shows an example for 41 Ari. In figure 7a) the primary star is already positioned in analyzer F2 but the contrast isn't yet adjusted with polarization filter F1. In figure 7b) contrast is adjusted to component D with F1. After recording the measurements a record with star drift for position correction will be made. After these records the next star of interest can be selected by Redshift software which will be used for position control of the telescope.

Figure 7 shows 41 Ari a) without contrast adjustment and b) with adjusted contrast of primary component by polarization filter. Exposure time was 0.5 s. Both pictures are stacked images of 100 frames.

Another example is the well-known binary Castor (figure 8). Components A (1.93 mag) and B (2.97 mag) are much brighter than faint components C (9.83 mag) and D (10.07 mag). For measurements of C and D the brightness of AB was reduced. In this case AB becomes separated and it is easy to measure the distance between AC and AD.

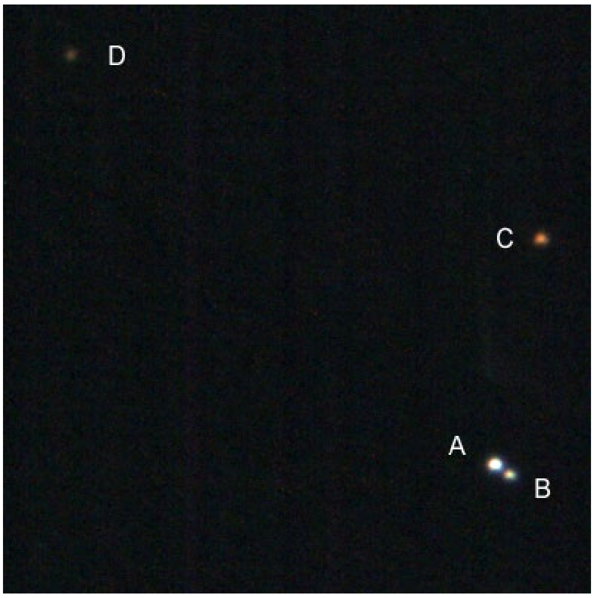

Figure 8 shows adjusted image of Castor. Because of intensity reduction for AB all components are clearly separated and distances between them can be measured. Exposure time was 0.25s

As already mentioned in section 2.2 the final image contrast depends on Δm between primary and secondary component. For large Δm double stars like γ Com (SMR 58) or Sirius the brightness of the primary has to be strongly reduced. Figure 9 shows the image with reduced brightness for γ Com (SMR 58), figure 10 shows the image with reduced brightness for Sirius A.

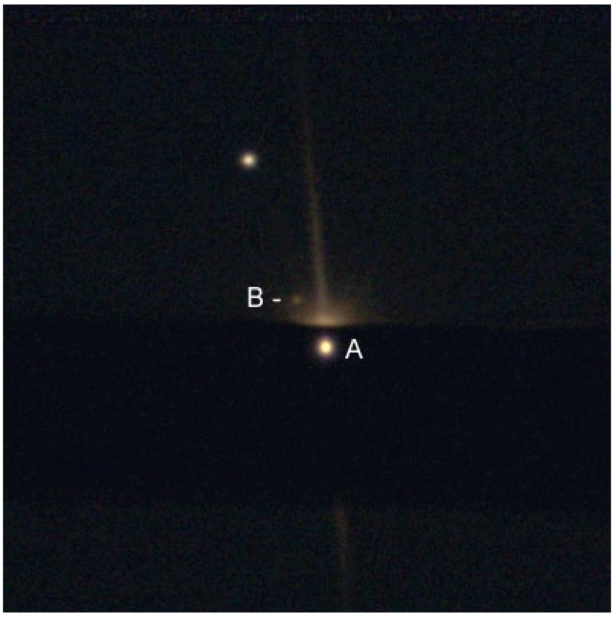

Figure 9 shows γ Com (SMR 58) with reduced brightness for the primary component. Δm is 7.6 magnitudes. Exposure time was 2s

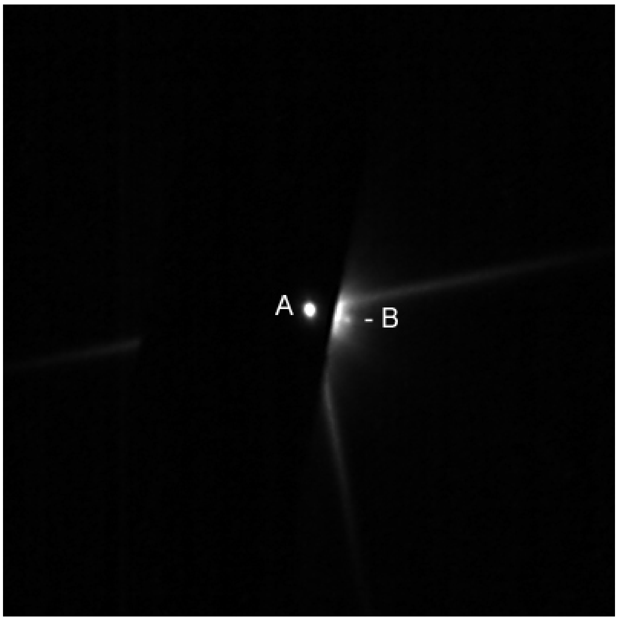

Figure 10 shows Sirius AB with reduced brightness for the primary component. Exposure time was 1/8 s

5. Conclusions

The HCDSF instrument offers a good alternative for occulters with fixed brightness reduction. Because of adjustment of the primary's reduction, exposure times for each double star system can individual be chosen. Exposure time depends only on weakest secondary component which should be measured, not on the primary's reduction.

With the carbon fiber reinforced plastic tubes the instrument is insensitive against temperature changes. The tubes offer high stability even if the filter unit is only connected with 3 tubes to the ocular adapter.

Because of the optical relay system the overall size of the instrument is very large. The aperture of the achromatic lenses is 12.5 mm, but the diagonal of the image plane is only 3.2 mm. Achromatic lenses with smaller aperture would have less focus length by same focus ratio. This would decrease the overall size of the instrument, the weight and especially the torque on the telescope's ocular adapter.

Except polarization filter based on reflection there are also polarization filter based on absorption. Contrast of these filters is only 1:7.500 instead of 1:100.000 but it would be good for most cases. With absorption-based polarization filter the entire contrast could be approved. Also it would be possible to place the polarization filter F1 behind the analyzer F2 between both achromatic lenses. Most important part would be an improvement of the analyzer F2 itself. A smaller filter with clear edges would be needed for measurements of doubles closer 10 arc seconds.

The HCDSF instrument has proven itself several times in practice. Despite its length and weight, the filter shows very good stability and high reliability on the Newtonian telescope. As described in some sections above there is still some space for improvements.

Acknowledgements:

This research has made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory.

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