Feasibility Study:
New NOT Adapter

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1 History

The present NOT Instrument Adapter was designed in 1987 by Ralph Florentin (optics) and Per H. Jensen from the Risø Group, built in 1988 in the workshop at Brorfelde Observatory and mounted in 1989 at the Nordic Optical Telescope.

2 Present design

The NOT Adapter is fairly large, the mass is about 1100 kg and the volume is Ø1200mm x 400mm. All parts are made in steel.

The Adapter is built of 4 main housing parts:

1. Interface part to the telescope, which includes: cable wrapping, rotator motors, support of the outer ring of the Ø1075 mm rotator bearing, support of brakes and encoder.
2. Rotating part is mounted to the inner ring of the bearing on one side, gearwheel on the Ø1200 mm edge and base for all adapter functions on the other side. Across this surface a 26 mm high rib is welded in the shape of a Ø1160 circle, truncated with two parallel sides 305 mm from the optical axis.
3. On the rib a 180mm high shield is mounted which support stand-by instruments and the electronics boxes used to control the adapter and the rotator functions.
4. A 20 mm steel plate close the shield and is mounting plate for Casegrain instruments.

The space envelope inside the adapter is 194mm in the Z direction. The present adapter is designed to carry the weight of 250 kg at a distance of 500 mm from the Cassegrain mounting flange, i.e. torque limit is 1250 Nm.

3 New Adapter

The new adapter housing cannot be much different from present one. Some changes to the shield and mounting plate for Casegrain instruments can be implemented but the main parts should not be changed. Therefore the suggestion to a New Adapter design is to make new internal units inside the present housing. It is foreseen that a new adapter shall have following functions, also outlined in figure 1:

1. An auto-guider system
2. A 45 deg. mirror carriage, for stand by instruments,
3. Fibre Link.
4. Two channel stand-by CCD camera.
5. Port for future instruments, e.g. a stand-by spectrograph.

4 Auto-guider

The motivation for an upgrade of the guider system is mainly due to wide-field instruments arriving, restricting the field of the current guider to a point where the chance of finding a suitable guidestar becomes low.

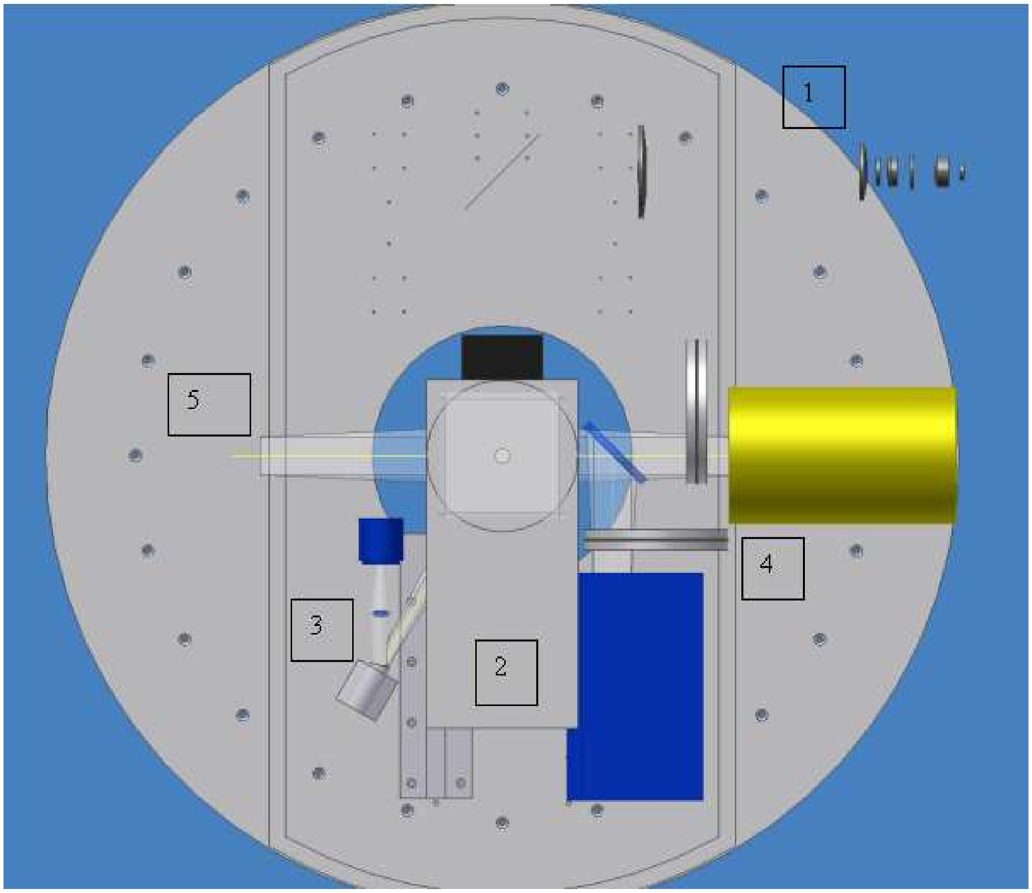

Figure 1: View against M1 cell, Cassegrain mounting plate removed.

4.1 Field of view for guiding

The area that can be used for guiding is restricted near the optical axis of the telescope by the requirement for an unvignetted light path to the science instruments, and at large field angles by the telescope, primarily due to vignetting, but also from field aberrations.

The largest fields of instruments in operation are 6'5x6'5 for ALFOSC and 7'7x7'7 for MOSCA. In the future, the field requirement will increase strongly by the introduction of FRED with a 17'5x17'5 field.

Another constraint is the expected increase of the size of a diagonal mirror in the adapter, feeding stand-by instruments.

On the outside, the field is vignetted by a "collar" going through the central hole of the primary mirror. The unobstructed beam has a radius of 12'5. Outside this, the throughput falls off approximately linearly and reaches zero at a field angle of 24'. This is illustrated in figure 2. In fact, the present field is slightly smaller, as the 270mm diameter of the collar is reduced by about 10mm by the inserted makeshift baffle.

A more detailed vignetting map is shown in figure 3. The MOSCA and FRED science fields are shown, along with their requirements for unobstructed area at the height of the inner floor of the adapter, 226mm above focus. Also shown is the unvignetted field of the telescope, along with regions of 12.5%, 25% and 50% vignetting.

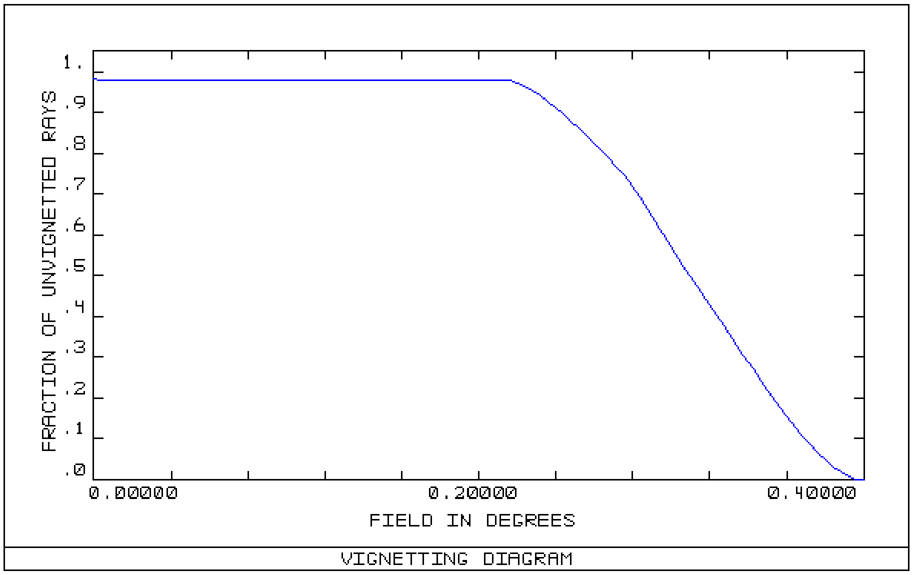

Figure 2: Vignetting versus field angle for NOT.

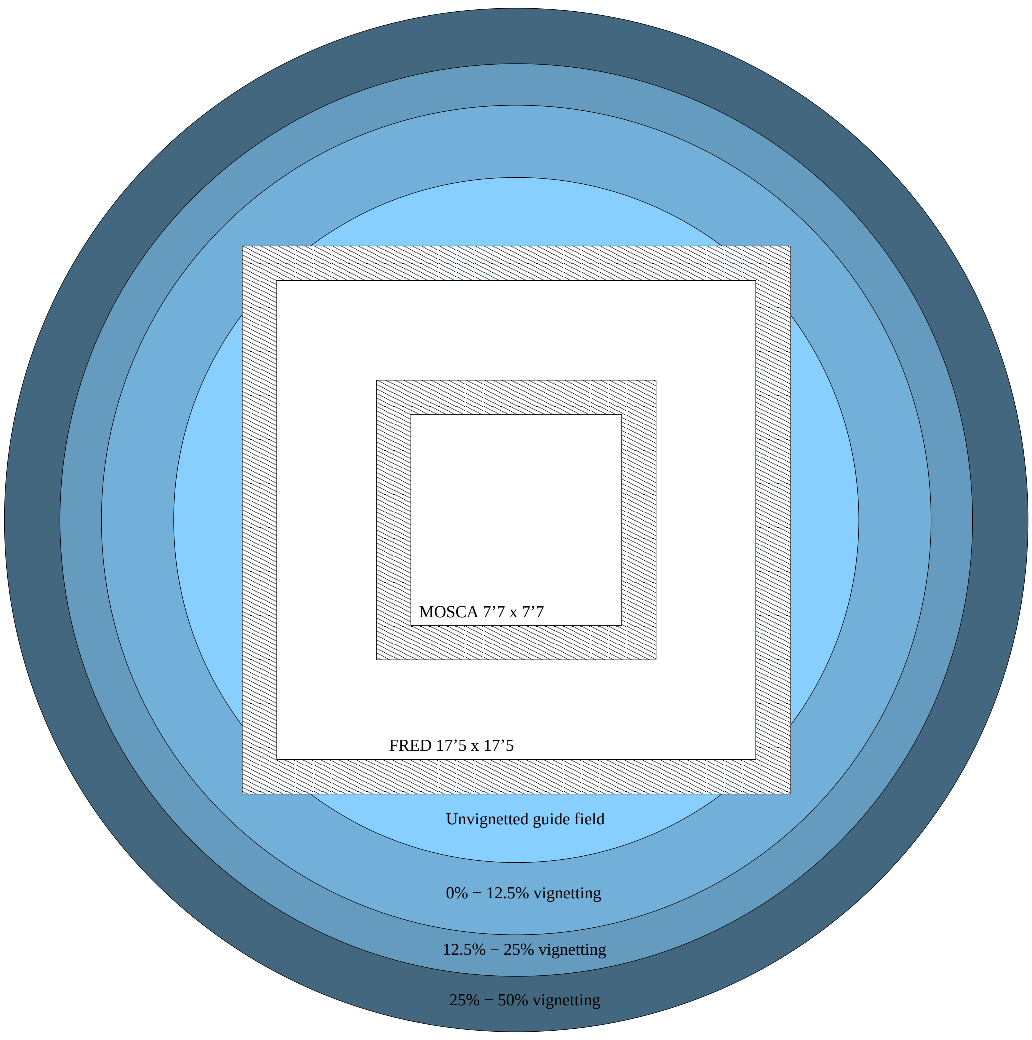

Figure 3: Vignetting map for the inner floor of the adapter.

4.2 Focal reducer guider

The moving guide probe currently installed will not be considered in detail here, as it is relatively easy to install, and it has already been treated in [Cox, G. 2003]. As an alternative, a stationary guider with a large field of view is considered.

The proposed guider has a large stationary pick-up mirror near the edge of the science field, followed by focal reducer optics and a relatively large CCD camera.

There are pros and cons of each system. Among the advantages of the focal reducer guider are:

- No X/Y movement, improving reliability.
- Correction of field aberrations, improving off-axis guiding.
- Option for auto-focus of telescope, using a focus pyramid.

Some disadvantages:

- Unable to view science field due to fixed off-axis field.
- No video-rate display, at least with suggested CCD and controller.
- Optical complexity.
- Lower throughput, restricted to 550nm - 800nm.

Room requirements are near break-even. The moving guide probe is relatively compact, but requires a lot of room to move about, while the focal reducer has some large, but stationary components.

4.3 Limiting guide star magnitude

The prediction of the faintest useable guide stars for the camera is based on the following: The camera is equipped with a KAF-3200E CCD, which is a front side illuminated detector with a relatively high QE, peaking around 65%. An even more efficient version with micro-lenses is available, but this is not evaluated. The guide frequency assumed here is 1Hz, although image rates in the 0.1Hz to 4Hz range are expected to be available. 1Hz seems like a good compromise between sky coverage and response time. The camera has a read-out noise of about 10e$^-$, and a dark current of about 7.5e$^-$/pix/sec at 19°C. The pixel scale is assumed to be 0.33 arcsec/pixel. Binning is not used. For reference star signal, V-band ALFOSC data are used. This includes telesope efficiency, and the throughput of the focal reducer is expected to be similar to ALFOSC. The guider uses the 550nm to 800nm range, i.e. the V, R and some of the I band. A somewhat pessimistic extrapolation of the data is used here, assuming the same star and sky background flux at the longer wavelengths as for the V band, while the conditions in the red in reality are expected to be more favourable. Sky backgrounds for dark time (m_V=21.8/"^{2}), full moon (m_V=18.5/"^{2}) [TNG WWW] and a guess of the sky brightness with cirrus at full moon (m_V=16/"^{2}) are investigated in different seeing conditions. The required signal to noise ratio is derived from experience with HiRAC, where a $S/N \geq 4$ per quadrant was required. An algoritm determining the centroid in a small image will require a better signal.

The graph in figure 4 displays the results. It appears that stars of m_V=17 will allow guiding in quite adverse conditions.

4.4 Sky coverage

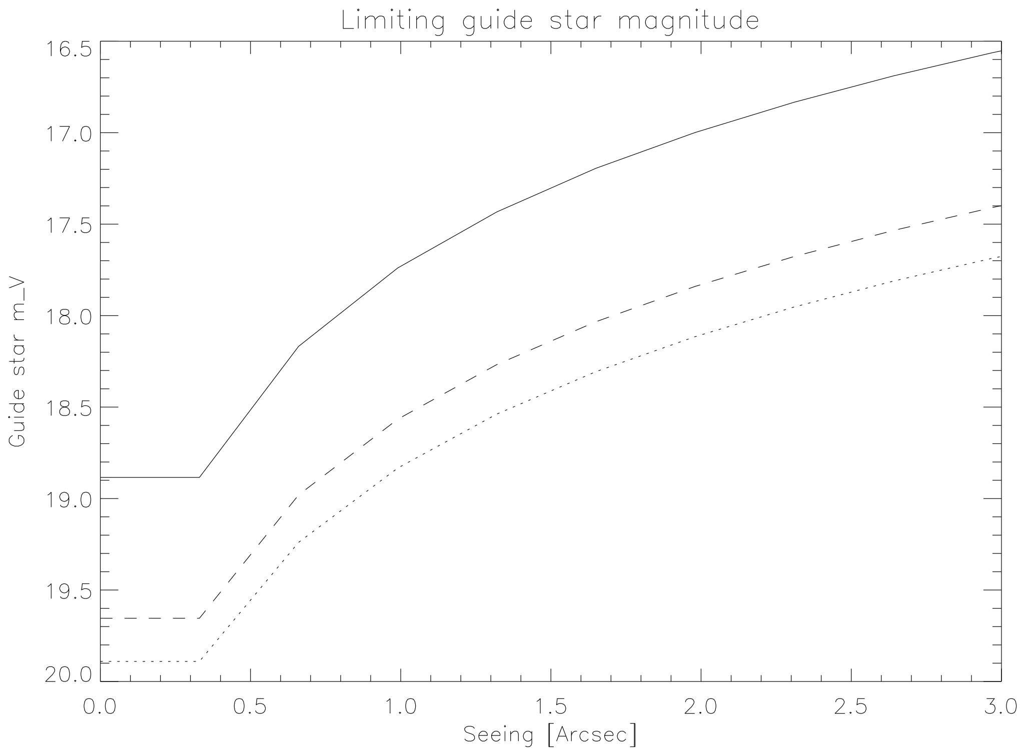

Figure 4: Limiting guide star magnitudes for 1 sec exposures in different seeing conditions and for three sky backgrounds: Dotted graph is for dark time, dashed line for full moon and full drawn line is an estimate for some cirrus during full moon.

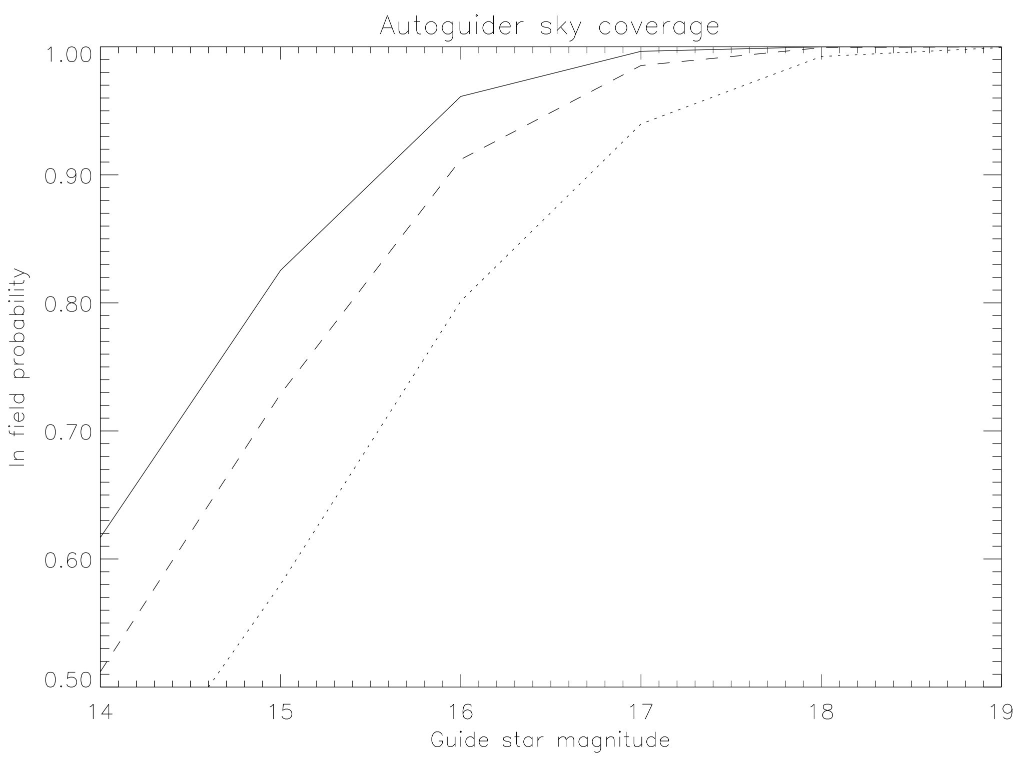

Figure 5: Probability of finding a star of given magnitude near the galactic north pole, with a field of 67 square arcminutes (full line), 50 square arcminutes (dashed line) and 33 square arcminutes (dotted line).

The probability of finding a star suitable for guiding near the galactic north pole is plotted in figure 5 for field sizes of 67, 50 and 33 square arcminutes. Star densities are from [Allen 73]. In the previous section it was concluded that a guide star of $m_V = 17$ would be sufficient. A field of 67 square arcminutes will give a 99.6% probability of finding a star of $m_V = 17$ or brighter, even at the galactic pole. Reducing the field size to half of this considerably lessens the probability of finding a guide star, as demonstrated in the graph. In conclusion, the field avilable for finding guide stars should not be significantly less than 67 square arcminutes.

4.5 Focal reducer guider concept

The guider consists of a pick-up mirror, one or more folding mirrors, a collimator and a camera with a KAF-3200 CCD. The required reduction in image scale is 5.5, resulting in a final focal ratio of 2.0.

In [Cox, G. 2003] and [Cox, G. 2004], a guider of this type with a demagnification factor of 6.6 and a larger, more elongated KAF-6303 detector is considered. This is discouraged, as the size of the optics would be prohibitive.

The general layout is shown in figure 6. The collimator contains two elements, with the first necessarily being quite large with a diameter of about 140mm. The camera is made from a doublet and three singlets. The elements of the guider have lateral offsets in some places, which makes the focal reducer able to partially compensate for the field aberrations of the telescope. In the collimated beam, a filter allows passage of wavelengths from 550nm to 800nm. Outside this range, the optical quality rapidly degrades, so operation without the filter will not be useful.

As an option, a focus pyramid can be inserted in the collimated beam, producing four guide star images. This can provide auto-focus for the telescope, but requires guide stars about one magnitude brighter. In the vignetted part of the guide field, it is perhaps not feasible to properly calibrate the autofocus signal.

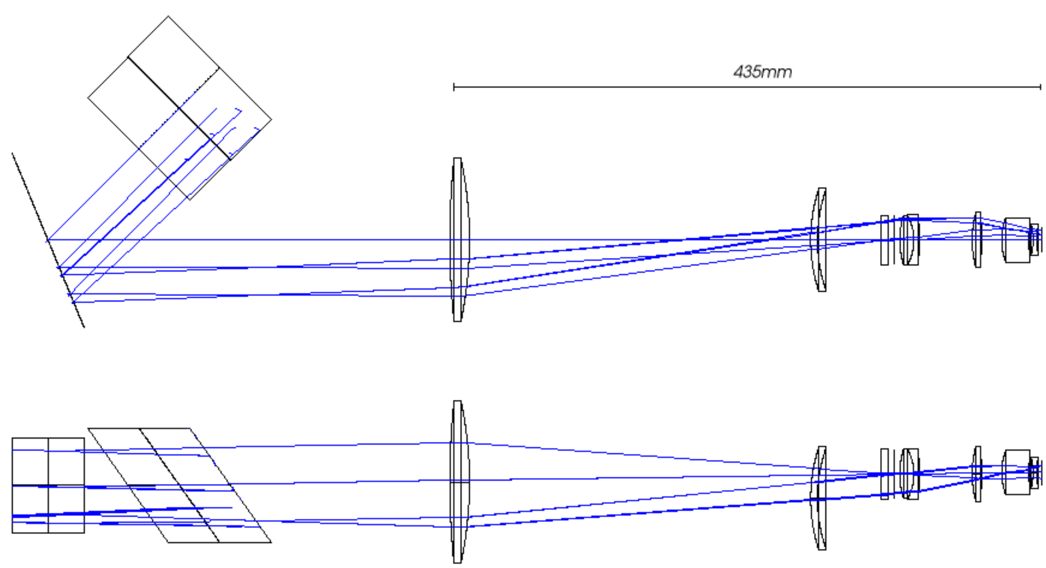

Figure 6: Top and side view of the optical layout of the focal reducer guider, with examples of pick-up and folding mirrors. After the two elements of the collimator, a bandpass filter and an optional focus pyramid is placed. Following that is a five element camera. Note the offset elements on the lower figure. Rays are only shown for half of the symmetric field.

An example of a polychromatic spot diagram is shown in figure 7. Nine guide field positions are shown, from the axis of symmetry of the field, and out to one side. The average spot FWHM is 2 pixels or 0"55 - not exceptionally good, but adequate for guiding.

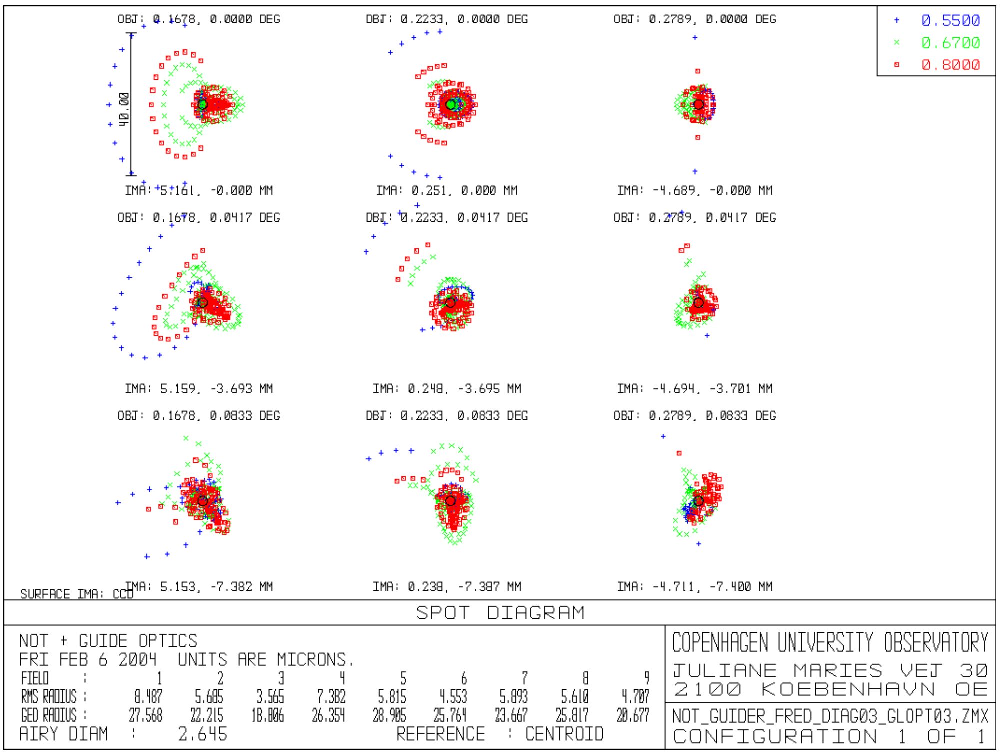

Figure 7: Polychromatic spot diagram for nine field positions. The calculation is for the pick up mirror placed diagonally to FRED.

4.6 Guider with no FRED vignetting

With the requirement of a 67 square arcminute guide field, the aspect ratio of the CCD makes this a 10 by 6.7 arcminute field. From figure 3 it is clear that it is not possible to place a field of these dimensions without causing vignetting of either the FRED science field or the guide field.

The field is directed to the guide optics by a pick up mirror. The mirror should be placed as close as possible to the focal plane to minimise vignetting, and especially the side of the mirror closest to the science field should be placed low.

This suggests that the light path should be reflected across the telescope axis by a 45°mirror. Unfortunately, this is not possible as the broad beam would be partially blocked by the mirror assembly for the stand-by instruments. In stead, the light has to be directed outwards, which forces the pick-up mirror further away from the centre, as the innermost edge of the mirror is further away from focus. Also, the mirror has to be placed higher in the adapter to make room for the assymmetric optics in this orientation, which moves the mirror out even further and requires a larger mirror.

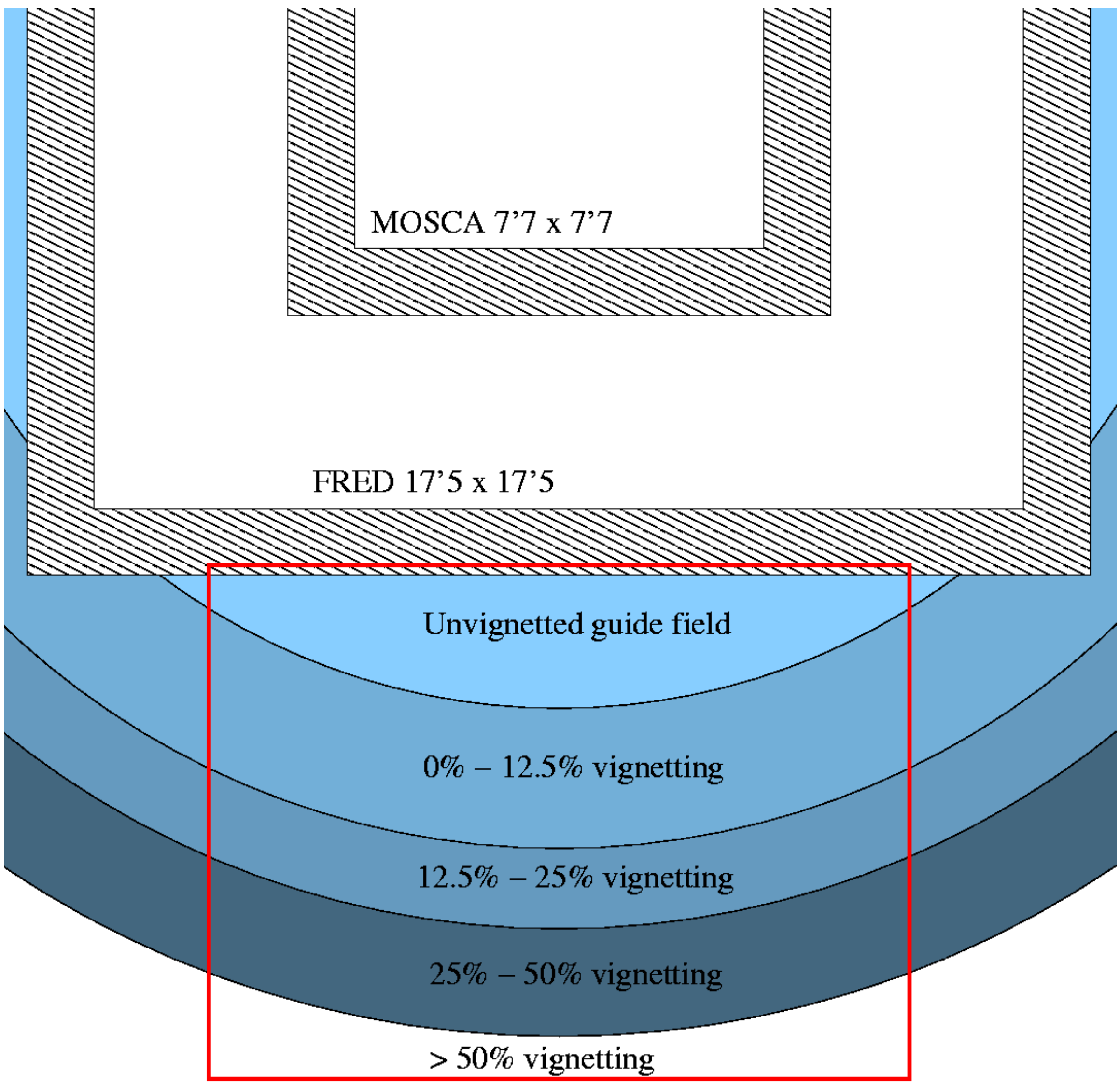

Figure 8: The rectangle marks the pick up mirror placement for a guider that does not obstruct the FRED field.

The proposed placement of the pick-up mirror is shown in figure 8. The positioning is calculated for a 17 arcminute science field, so the outermost 0.25 arcminute of one side of the

FRED field is slightly vignetted. On average, the guide field is about 25% vignetted by the telescope structure, with only 39% throughput in the worst affected corners.

This increases the risk of not finding a suitable guide star to at most 2%, but using another rotator field angle should eliminate the risk. Even for spectroscopy, two rotator angles should always be available.

4.7 Guider with partial FRED vignetting

In order to reduce the vignetting of the guide field and thereby improve sky coverage, one may accept vignetting of a part of the FRED field. It turns out that by placing the guider mirror along the diagonal of the FRED field, the guide field can get closer to the optical axis and a relatively smaller area of the FRED field is vignetted, compared to a mirror with similar guide star throughput placed along the side of the FRED field.

The acceptable vignetting was defined to involve exacly half the area of one of the quadrants, or 12.5% of the total FRED field. Only 2.5% of the FRED area is completely blocked, and the partially blocked field may still be of use, although with reduced quality.

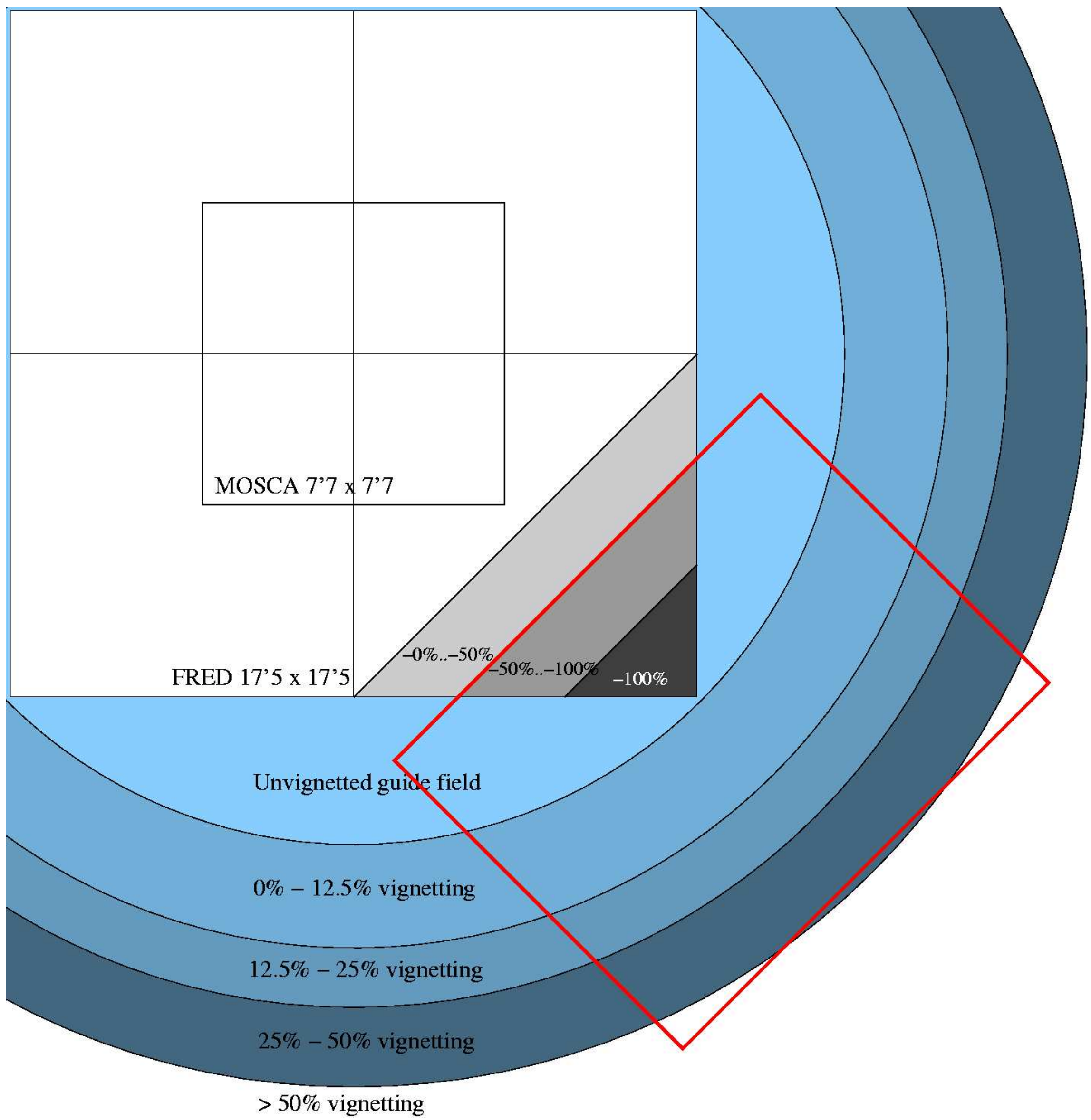

Figure 9: Guide mirror placed diagonally, partially vignetting the FRED field, as shown by the shaded area. The MOSCA field is not disturbed.

The placement of the guide mirror in this configuration is shown in figure 9. The improvement in throughput to the guide field is not great: About 1/4 of the guide field is vignetted more than 25%, compared to about 1/3 of the field in figure 8, with practically no vignetting of the FRED field. The small improvement will be more pronounced when considering the further restriction of the field from the modified baffle.

A disadvantage of this design is that the corners of the guide mirror will cause vignetting of the output beam from the stand-by mirror in the two 90 degree orientations adjacent to the guide mirror.

4.8 Guider with image slicer

Good sky coverage can be achieved by using multiple pick up mirrors to combine the unvignetted field onto a single detector.

Here the probably simplest version of the multiple mirror option is examined, combining only two fields. The concept is shown in figure 10: Two pick up mirrors are placed on one side of the FRED field, each covering a field of 3'33 by 10'. Although each mirror is only covering half of the field of the single mirror option, the mirrors still need to be quite large, due to the distance of about 265mm to focus. The somewhat smaller size of the mirrors in the direction perpendicular to the optical axis makes it interesting to attempt to direct the reflected light across the optical axis, below the stand-by mirror. Directing the light inwards allows positioning the mirrors very close to the adapter floor and closer to the field centre. The mirrors are as a first approximation tilted 45 degrees, but in addition needs to be tilted to converge on the following set of mirrors.

The next set of mirrors are folding mirrors, one for each pick up mirror, directing the combined light to the focal reducer optics. The two mirrors are placed on top of each other, individually tilted to compensate for the angle of incidence from the pick-up mirrors. The mirrors are placed near the focal plane to allow them to be as small as possible. This is important in order to direct the light below the stand-by mirror and to effectively use the field of the guide camera.

As can be seen from the figure, there is still vignetting of the guide field in this configuration, and the throughput will be somewhere inbetween the two previously presented configurations. There is also a slight vignetting of the FRED field at the extreme corners, considered to be hardly noticeable.

Due to the discontinuity caused by the two fields, the optics cannot correct field aberrations quite as well as the single field designs. The so far best design has a spot FWHM of 3.3 pixels.

By replacing one of the collimator lenses by a cylinder lens, the FWHM can be improved to 2.8 pixels, still considerably worse than the layout with one pick-up mirror.

At the end of this study, it was found that the layout was not compatible with the stand-by mirror, as much of the guide star light would be blocked by it. Probably a similar layout placed as high as possible in the adapter could be fitted in, but with somewhat more vignetting than shown in figure 10. The alternative of the first mirrors directing the guide light away from the centre does not seem attractive, mainly due to the room requirements of the following pair of folding mirrors.

4.9 Recommendation

Three designs of an autoguider camera with a fixed pick-up mirror have been presented. All of these suffer from vignetting, but still in the worst case condition evaluated, the probability of finding a suitable guide star is estimated to be 98%.

The efficiency of the three guider designs are not much different, so the recommendation on which to use rather relies on their compatibility with other telescope components. The diagonally positioned guider has the drawback of relatively strong vignetting of the FRED field and bloking of the light path in two of the positions of the stand-by mirror. The guider with a two-mirror pick-up field will suffer from vignetting from the stand-by mirror, and the design

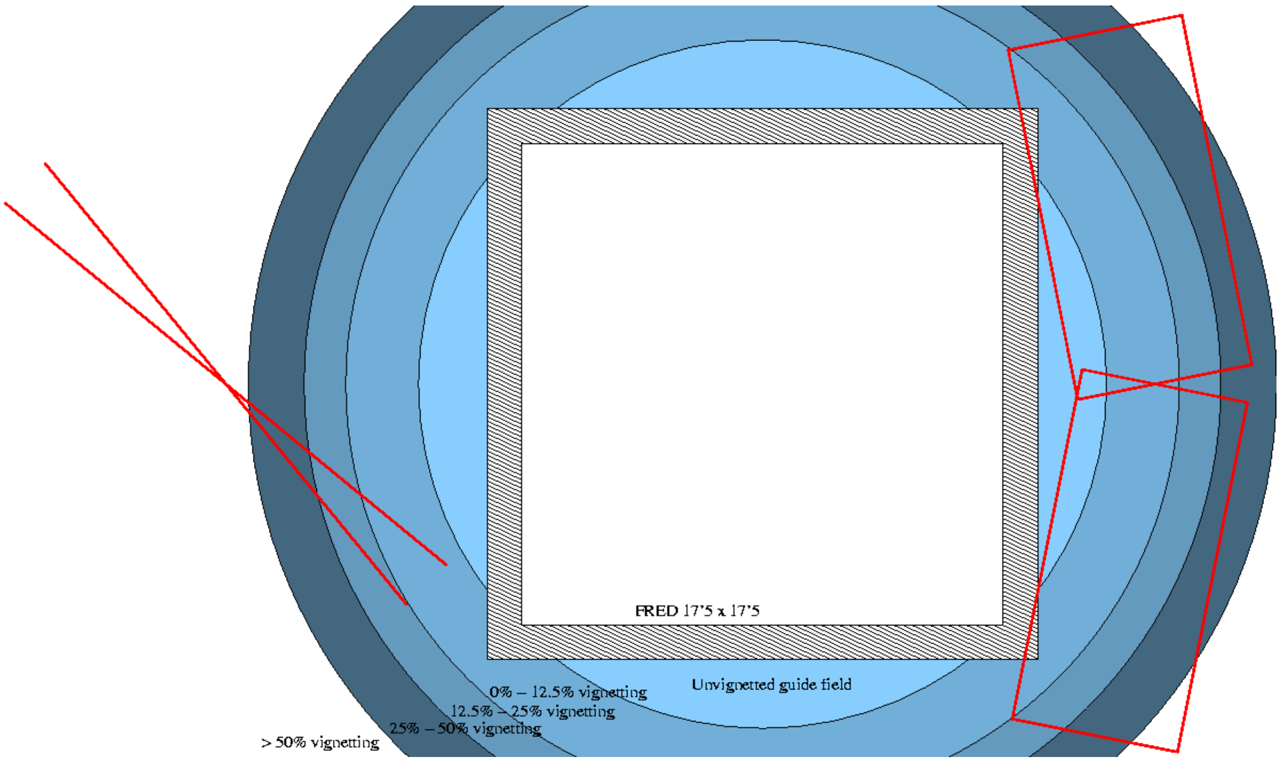

Figure 10: Mirror positions in the image-slicer guider. On the right side, two mirrors pick up a part of the field, and directs the light across the field to two folding mirrors on the left. The focal recucer optics wil be above the figure to the left.

has a relatively poor image quality. For these reasons, the first layout with one pick-up mirror placed along the edge of the FRED field is recommended.

The predicted guider performance depends strongly on the vignetting at large field angles. It is recommended that measurements are made to verify the amount of vignetting, e.g. by examining defocused images with the existing autoguider.

5 The 45 deg. mirror carriage

The carriage supports a 100 mm x 141 mm 45 deg mirror for directing the telescope field to stand by instruments. The mirror carriage will move in/out across the field over a range of about 200 mm in less than 50 sec.. The movement has to be locked when the carriage is in.

On the top of the carriage a rotator allow the mirror to feed 3 stand-by positions. Depending on choice of guide system some intermediate positions can be implemented. High precision of the rotation is required, which can be achieved by balancing and preloading the wheel.

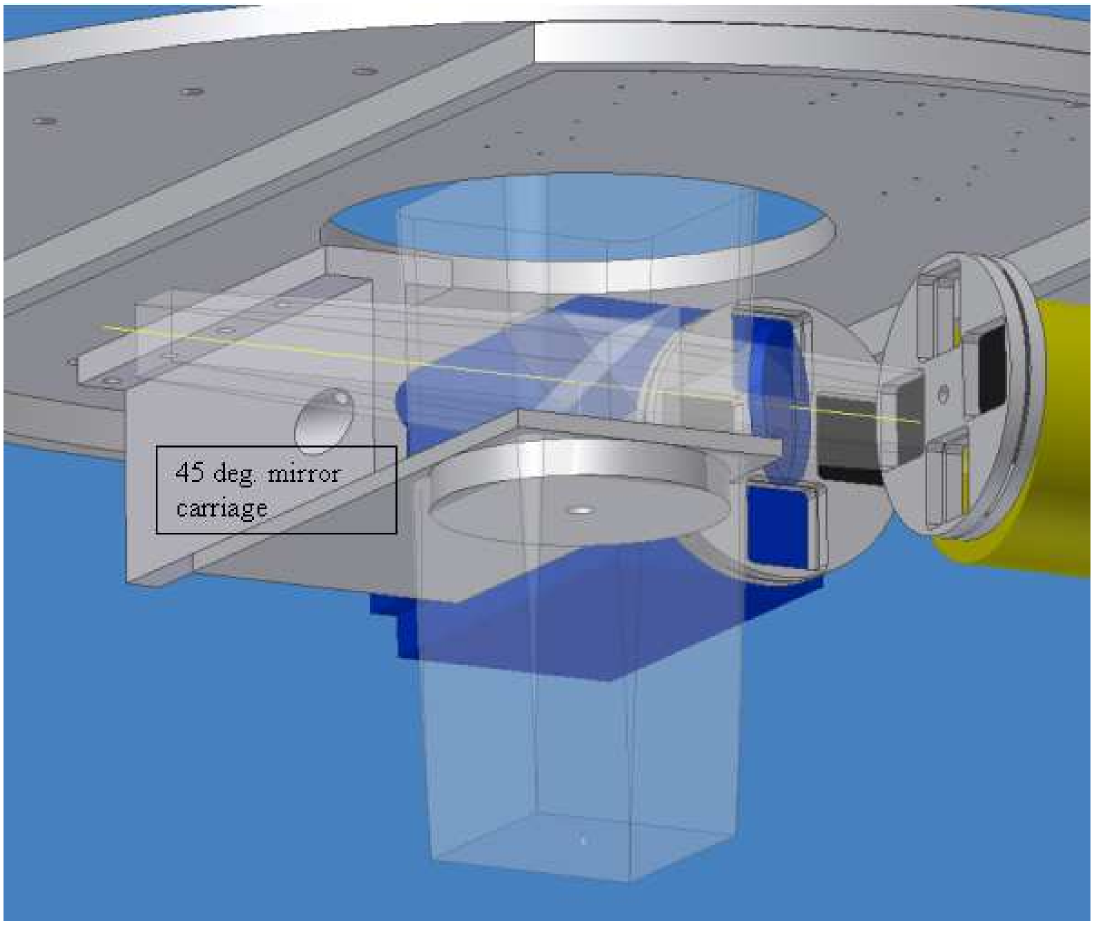

Figure 11: Isometric view of the 45 deg. mirror carriage, FRED science field, and stand by CCD Cameras View against M1 cell, Cassegrain mounting plate removed.

6 Two-channel stand-by CCD Camera

The field size in the stand by CCD Camera is intended to be 50x50 mm, i.e. 6.1 arcminute side length in both channels, suitable for the proposed 12μ $4K^2$ detectors. Larger detectors would not be compatible with the proposed design.

176 mm from stand by foci the beam is divided by a Ø110 mm dichroic. One surface of the dichroic will have to be figured to minimise aberrations, or a cube may be used. Six 60 mm square filters and one free position are available for each channel, implemented via double filter wheels. Installing other filters will require removing the adapter bottom plate. Each channel has a butterfly shutter. All movements are performed by stepper motors. Both cameras shall have their controllers outside the walls and will allow evacuation from outside.

7 Stand By Fibre feed for FIES

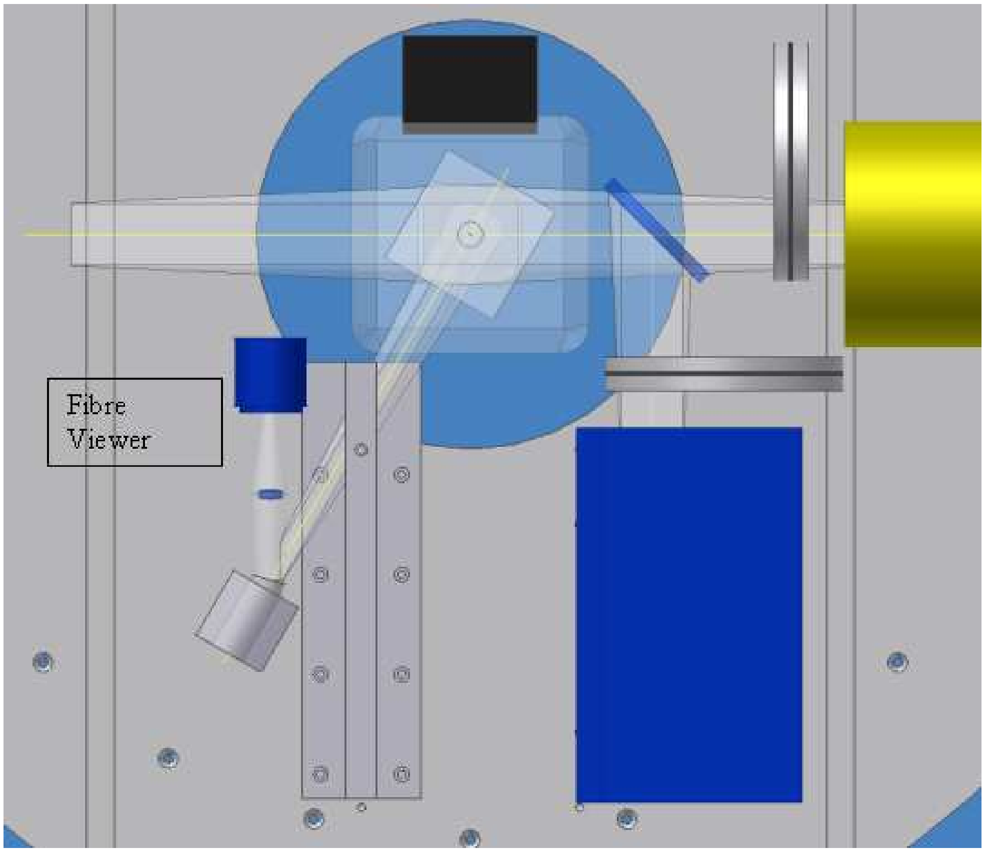

Figure 12: The fibre end mount with fibre-viewer camera, 45 deg mirror carriage removed

When the 45 deg. mirror is in and rotated 30 deg, the object is projected onto the fibre end, as shown in figure 12. The fibre is mounted in the centre of a mirror Ø20 mm, which is tilted 15 deg. to direct light to the fibre viewer camera. The fibre entrance is re-imaged onto the viewer CCD with a F/8.4 beam, giving a field size of 2.0 arcminutes and a sampling of 0"23. The suggested camera is a SBIG ST-9XE with a 512x512 pixel CCD.

Another layout considered is to place the fibre end approximately 180°from the position in figure 12. This would allow one of the stand-by cameras to be used as slit viewer. However, this would place the fibre head where it could block the path of autoguiders of both focal reducer and X-Y carriage type.

8 Calibration unit

If calibration light sources in the adapter are required, a vertical mirror placed on the rear side of the 45 deg mirror carriage could be used for directing the calibration light to several stand-by positions. This would however not allow the calibration sources to be used from Cassegrain focus.

Ideally, a 45 degree mirror above the mirror for stand-by instruments could direct calibration light downward to Cassegrain focus or stand-by instruments. Such a mirror would have to be quite small, making it hard to use for flat-fielding, and a mirror in this location would perhaps interfere with the applications mentioned below.

9 ADC / Polarisation unit

Above the 45 deg mirror, from 358 mm to 408 mm above focus, 50 mm is available for installation of an ADC unit and/or a polarisation unit. Both units will require in/out movement and rotation. The maximum aperture diameter would be approx. 75 mm. The limited space makes it unlikely that both units can be used simultaneously.

10 Installation

Electronics Boxes: At least one of the el. boxes along both sides of the Adapter has to be moved to make adequate room for the auto-guider camera and for a stand-by spectrograph.

Downtime: It is our intention to make all the components in so few units as possible, the auto-guider, the stand-by CCD camera, the 45 deg mirror carriage and the fibre link, but at least 1 week will be needed for a team of 4 people for mechanical and electronic integration and test. The amount of software to change and integrate is not calculated at the moment.

11 Cost estimate

We estimate that the cost of the stationary autoguider will be around 100 kEuro. The cost of the two-channel stand-by camera will also be around 100 kEuro (including cryostats and controllers, but excluding CCDs, filters, dichroic and optics). We have not estimated the cost for the 45 deg mirror, the stand-by fibre feed, and the calibration unit, but a guess on these units together would probably be below 100 kEuro.

The prices quoted are only indicative and in no way binding for CUO.

Work could probably start January 1st, 2006, and be carried out over a period of 1.5 to 2 years.

References

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[TNG WWW] Telescopio Nazionale Galileo web site : **La Palma sky brightness**, http://www.tng.iac.es/info/LaPalmasky.html