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GREGOR:
Telescope Alignment (M1 – M3)

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Signatures & Approval

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Draft	2018-09-07	D. Soltau	New Document	
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Table of Contents

1 Scope

This document explains the alignment of the three curved GREGOR mirrors M1, M2, and M3. This alignment is necessary after these mirrors had been removed e.g. after recoating.

2 Introduction

For this document I discriminate between “Telescope”, “Coudé train”, and “AO relay optics”. See Figure 1. These three groups have to be aligned independently. They are connected by means of the mirrors M4 and M12. One of the system’s drawbacks is the fact that M4 has only two degrees of freedom, which makes it impossible to connect the telescope with the Coudé train without introducing slanted angles. This causes beam wobble. This document deals with the “Telescope” only.

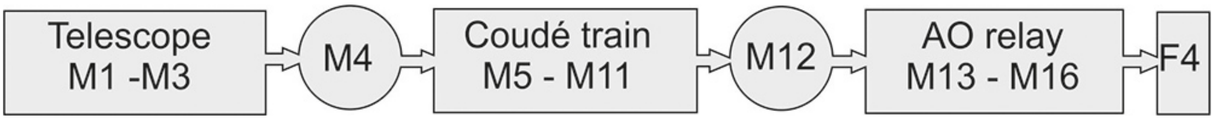


Figure 1: Raw scheme of GREGOR to the science focus F4

The telescope’s geometry is determined by

- The azimuth axis
- The elevation axis

They carry the telescope structure.

The manufacturer made sure that:

- The azimuth axis is vertical (0° w.r.t. gravitation)
- The elevation axis is horizontal (90.0° w.r.t. gravitation)
- Azimuth axis and elevation axis intersect

Note: This intersection point is the natural global reference point of the telescope. It is fixed in space. The center of the M4 plane is supposed to coincide with this point.

- The symmetry axis of the structure coincides with the azimuth axis when the telescope elevation is 90.0°

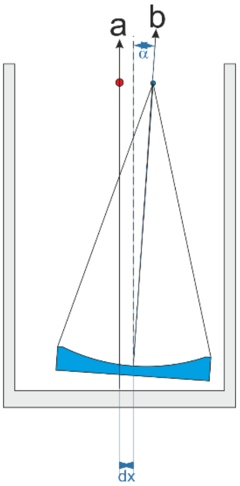


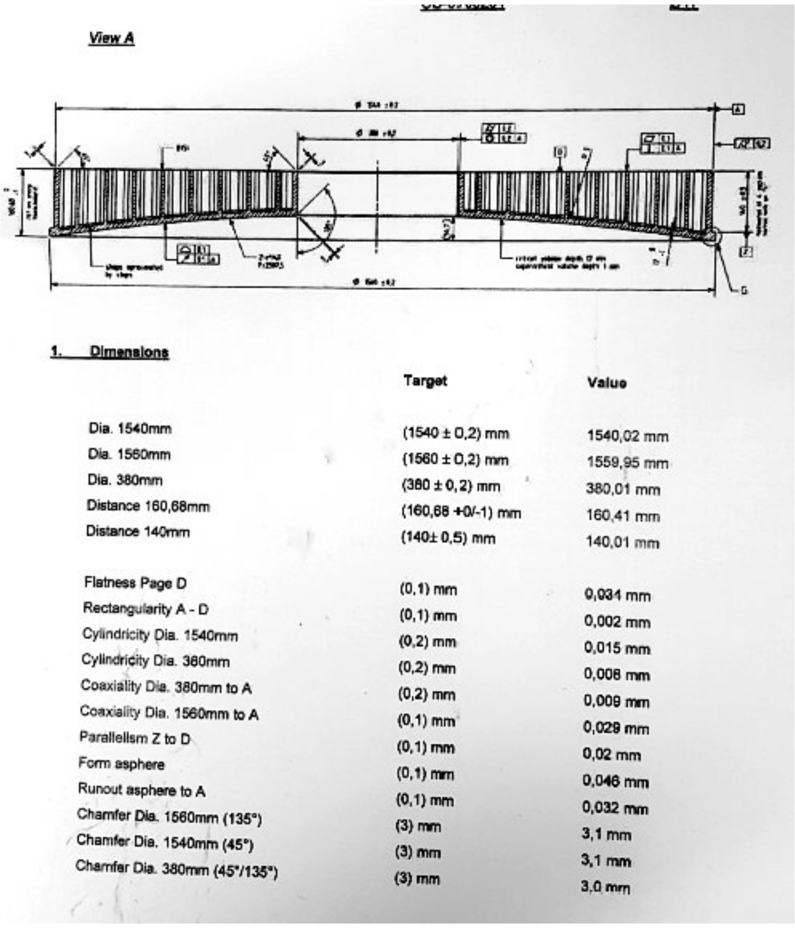
Figure 2: Possible misalignment of M1 w.r.t. the telescope structure

Figure 2 shows this in principle. M1 can be laterally shifted by a certain amount *dx* and tilted by a certain amount *α* so that the mirror looks into direction *b* whereas the structure points to direction *a*.

The goal of the alignment is to place M1 inside the telescope such that the optical axis of M1 coincides with the azimuth axis (which implicitly means that it coincides with the symmetry axis of the telescope structure.

3 M1 Dimensions

Figure 3 is a data sheet by Schott, which gives the dimensions of the M1 substrate. Note that the coaxiality of the central hole with the optical axis (Runout asphere to A) is only 0.032 mm. An overview of the fundamental parameters of M1 to M3 is given in Table 3 in Section 11.



1. Dimensions

	Target	Value
Dia. 1540mm	(1540 ± 0,2) mm	1540,02 mm
Dia. 1560mm	(1560 ± 0,2) mm	1559,95 mm
Dia. 380mm	(380 ± 0,2) mm	380,01 mm
Distance 160,68mm	(160,68 +0/-1) mm	160,41 mm
Distance 140mm	(140± 0,5) mm	140,01 mm
Flatness Page D	(0,1) mm	0,034 mm
Rectangularity A - D	(0,1) mm	0,002 mm
Cylindricity Dia. 1540mm	(0,2) mm	0,015 mm
Cylindricity Dia. 380mm	(0,2) mm	0,008 mm
Coaxiality Dia. 380mm to A	(0,2) mm	0,009 mm
Coaxiality Dia. 1560mm to A	(0,1) mm	0,029 mm
Parallelism Z to D	(0,1) mm	0,02 mm
Form asphere	(0,1) mm	0,046 mm
Runout asphere to A	(0,1) mm	0,032 mm
Chamfer Dia. 1560mm (135°)	(3) mm	3,1 mm
Chamfer Dia. 1540mm (45°)	(3) mm	3,1 mm
Chamfer Dia. 380mm (45°/135°)	(3) mm	3,0 mm

Figure 3: Dimensions of M1 given by Schott (substrate manufacturer)

4 Tolerances

Tolerances only become an issue when we see GREGOR's optical system as a whole. There are two effects:

- Image quality (e.g. expressed in terms of PSF, MTF, or Strehl)
- Image position as a function of telescope position (e.g. expressed in mm/hour)

The optical requirements determine the tolerances. To give an impression about the order of magnitudes Table 1 shows the nominal aberrations at science focus F4 for some decenter and tilt

Table 1: Effects of decenter and tilt on optical performance

Wavelength = 550 nm	**Astigmatism [wave]**	**Coma [wave]**	**Strehl**	**WFE [wave] (rms)**
M1 decenter = 0 mm, tilt = 0°	0.00 0.00	0.03 0.00	0.94	0.04
M1 decenter = 0.1 mm, tilt = 0°	0.42 0.00	0.03 0.12	0.63	0.31
M1 decenter=0 mm, tilt=0.005°	0.00 -0.90	0.26 0.00	0.22	0.19

From Table 1 it is obvious that the tolerances for a Gregorian are extremely tight. M1 cannot be positioned within these tolerances. Only M2 can be positioned with this accuracy by means of its hexapod support. The philosophy is therefore to position M1 as good as possible and apply minor corrections to M2 with the hexapod.

5 Determine Azimuth Axis

The alignment refers to the telescope structure. For the vertical telescope position (Elevation = 90°) the structure axis coincides with the azimuth axis. The encoders are accurate with a maximum error of 0.01 deg in elevation. This is why the azimuth axis has to be determined.

5.1 Preparations

Before doing the actual alignment, some preparations are necessary:

- Drive the derotator in “Park” position
- Flood Coudé tube
- Remove exit window. Be careful as the rubber with grease can fall on top of the derotator.
- Install crosshair at exit window flange. This is crosshair CH1. See Figure 4. A piece of millimeter paper is useful to provide some coordinate system

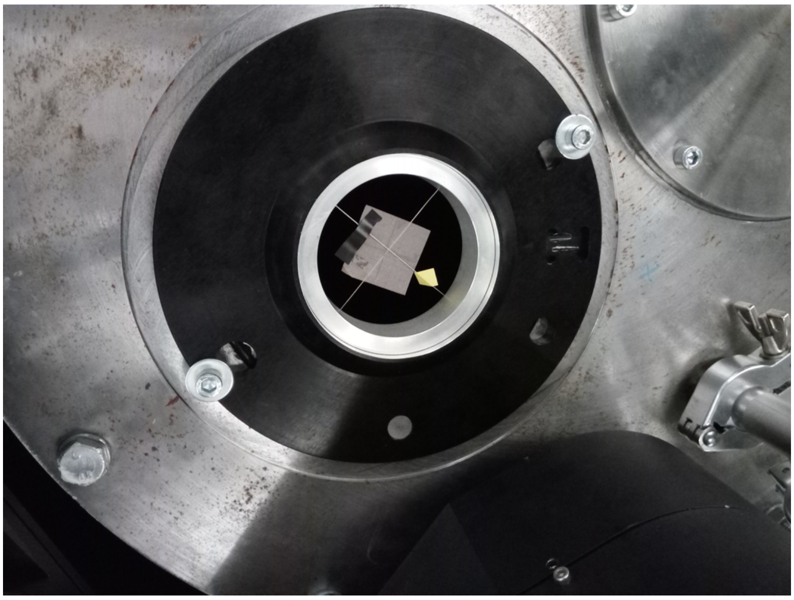


Figure 4 Crosshair CH1 at the exit window flange

Note: Previous measurements have shown that this crosshair coincides with the azimuth axis very well (within 0.2 mm)

- Remove cover plate on the floor (it generally should always be removed to equalize the pressure to the spectrograph room)
- Remove M7
- Move M16 and M11 out of the beam by driving them to their home positions.
- Open the M1 cover and insert crosshair in the central hole. This is crosshair CH2. See Figure 5

Figure 5 Crosshair in hole of M1 (CH2)

Note: According to the manufacturer the center of the M1 hole coincides with its optical axis by 0.01 mm

- Remove the calibration unit to have access to the flange and to have a free view on F1

Note: This flange close to F2 serves as a reference. Its center is assumed to lie in the mechanical axis of the telescope structure. Its plane is assumed to be perpendicular to the mechanical axis of the telescope structure

- Drive elevation to 90.00°

Note: At this position the F2 flange plane is horizontal. This can be checked with the precision vial

- Place the optical plummet below the CH1 on the spectrograph table and align the optical plummet such that the plummet is vertical and that CH1 is centered in the eye piece.
- Mount the 100 mm lens to the USB camera (µeye. ids) and focus to infinity.
- Place the USB camera (with lens) in front of the eye piece (see Figure 6).
- Check the position of the camera w.r.t. the eyepiece by focusing the plummet. The camera image must not shift laterally (boresight error) during focusing.
- Now you should see the internal crosshair and CH1 as a live image. Figure 7 shows what it should look like. The field of view corresponds to 12.5 mm x 10.0 mm at the exit window plane. It may be necessary to use a flashlight to illuminate the crosshair.

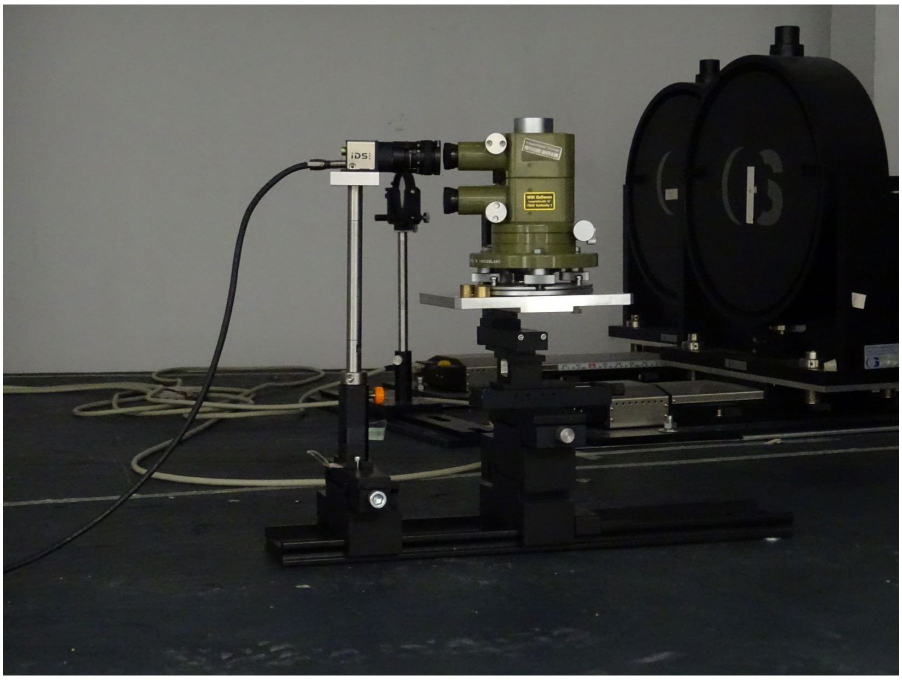


Figure 6: Optical plummet with USB camera on the spectrograph table

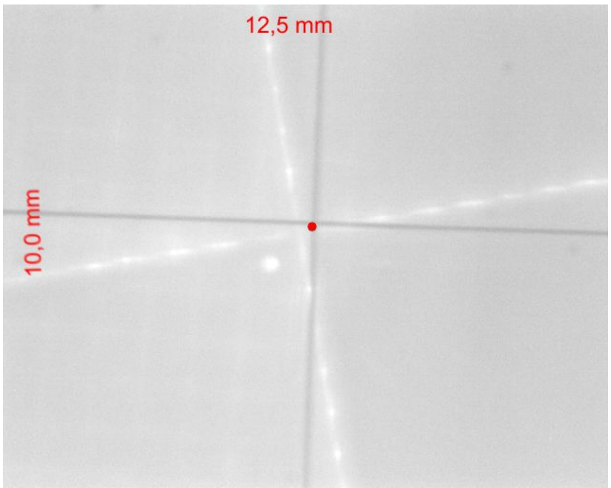


Figure 7: CH1 (bright), internal crosshair (dark), and FOV

5.2 Fine adjustment of the optical plummet

The goal is to make sure that the optical plummet's boresight coincides with the azimuth axis of the telescope.

For this purpose rotate the telescope in azimuth and take pictures. Figure 8 shows pictures for six different azimuth positions.

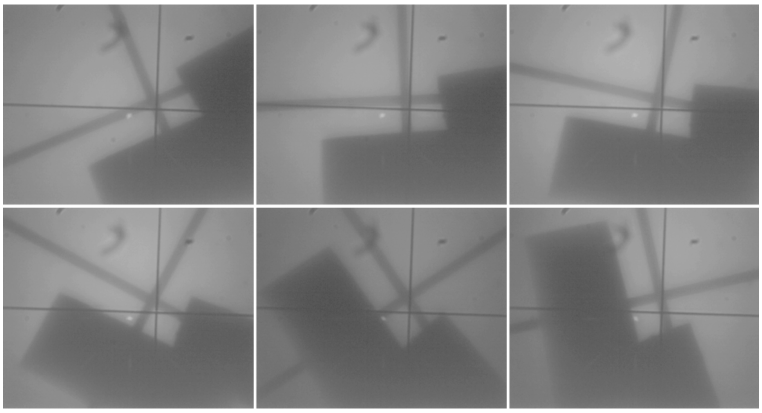


Figure 8 USB camera images for six different azimuth positions showing the crosshair at the exit window flange

Select a feature in the image and determine its position on the camera for each frame and calculate a least square fit circle. The center of this circle is the intersection of the azimuth axis in the plane of the exit window.

Figure 9 shows an example for such a circle fit and Figure 10 shows the result.

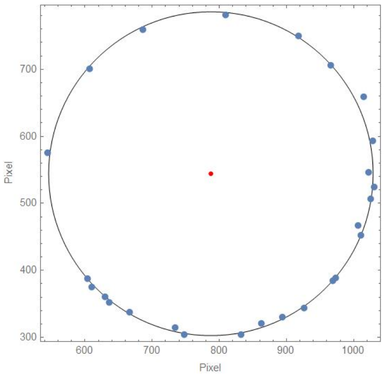


Figure 9: Circle fit for azimuth rotation

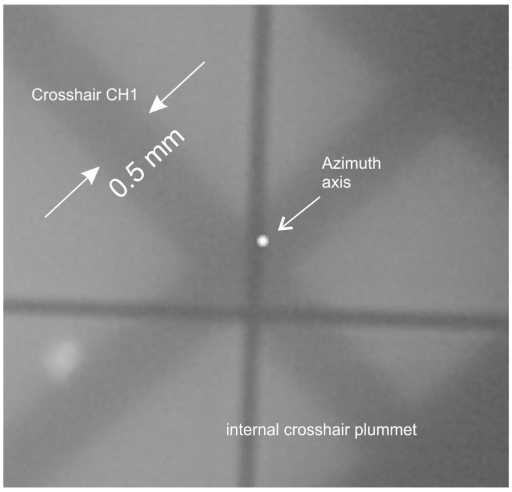


Figure 10: Result for circle fit: The white dot indicates the azimuth axis. It is about 0.2 mm next to the crosshair CH1. The narrow black crosshair is the internal plummet crosshair

Now the plummet can be shifted so that its internal crosshair coincides with the azimuth axis intersection and the plummet boresight represents the azimuth axis.

6 M1 Lateral Alignment

Create a target that defines a bull's eye at the crosshair center CH2 and proceed in the same way as with CH1. The result for August 2018 is shown in Figure 11.

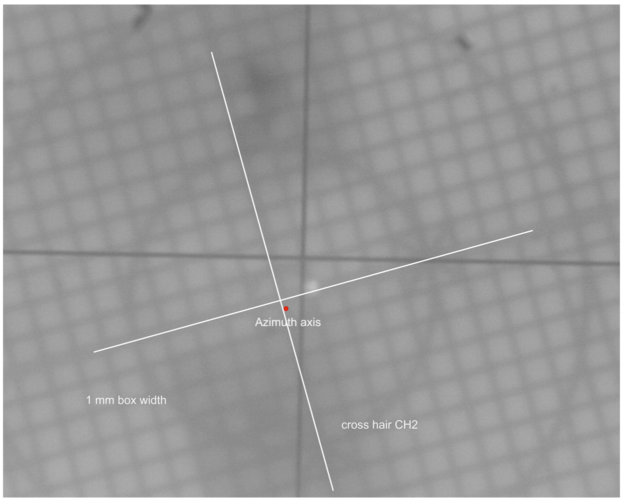


Figure 11: The white lines indicate the crosshair CH2 in the center hole of M1. The red dot indicates the intersection with the azimuth axis

In August 2018 the center of M1 coincided with the azimuth axis within 0.2 mm. This deviation matches the overall tolerance of the alignment procedure. Therefore we saw no reason to move M1 (which b.t.w. is difficult).

7 M1 Angular alignment

7.1 Preparation

First one has to make sure that the F1 field stop is in the center of the telescope structure. There is a laser mount with a central position and two off axis positions. In addition there are two precision lasers whose mechanical axis coincides very well with their optical axis (< 2/20000). See Figure 12.

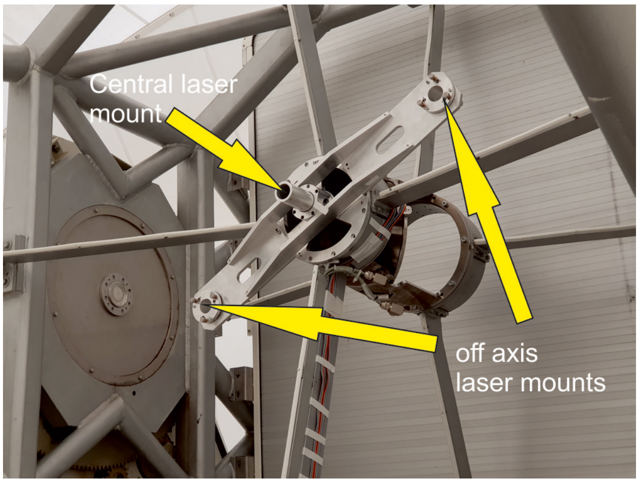


Figure 12: Laser mount at F2 flange

The central mount coincides with the structure axis when the laser mount is fixed to the F2 flange.

- Remove the calibration unit
- Mount the laser mount on the flange
- Put one laser in the central hole
- Check laser spot on CH2 (M1) and Field stop in F1

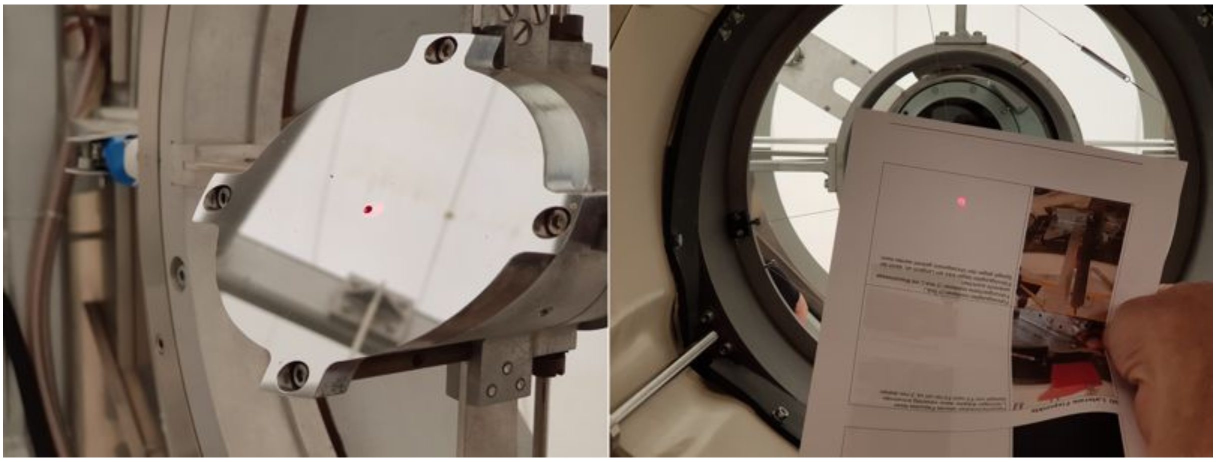


Figure 13: Central laser on F1 (left) and M1 (right)

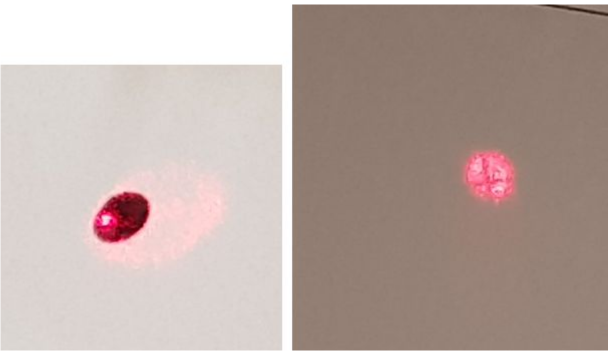


Figure 14: Magnification of Figure 13.On the left the F1 field stop together with the laser spot is shown. The (small) diameter of the field stop is 1.8 mm corresponding to 150 arcsec on the sky. In the right panel one can see the shadow of CH2 in the laser spot.

In August 2018 there was an offset of appr. 1 mm (corresponding to 83 arcsec on the sky) for the F1 field stop position and practically no offset for the M1 position (see Figure 14).

7.2 Angular alignment

Once M1 is in the correct lateral position one can take care about the tilt position.

- Take the laser bar and insert the central laser
- Place it on the VTT entrance window flange (see Figure 15)
- Align the second coelostat mirror so that the central laser is in autocollimation (see Figure 15)
- Put the two lasers in the outer positions and align the lasers so that both of them are in autocollimation

Now the laser beams are perpendicular to the central flange of the laser bar.

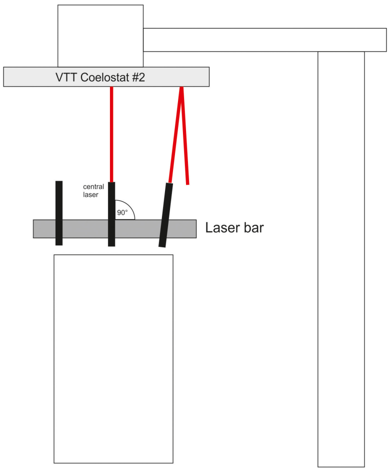


Figure 15: Setup for the laser bar alignment

Fix the laser bar with the two lasers in the aligned outer position on the F2 flange. See Figure 16. Be careful not to touch the lasers on the way from VTT to GREGOR, otherwise redo the alignment procedure.

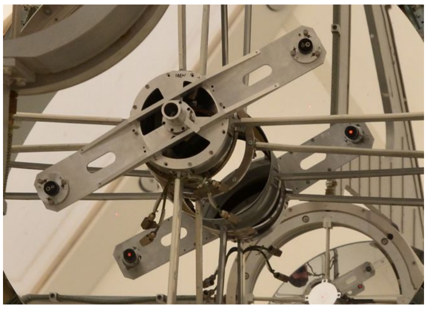


Figure 16: Two lasers for alignment mounted at the F2 flange

The two laser beams represent two parallel incoming beams and meet at the M1 focus. Now M1 can be tilted by shimming until the M1 focus coincides with the F1 field stop.

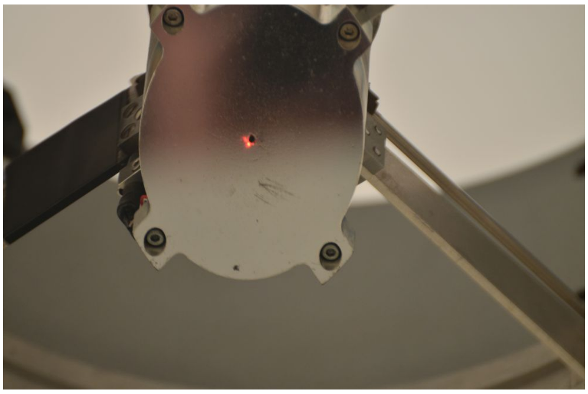


Figure 17: Two lasers meet (nearly) at the F1 field stop. Example from April 2017

Figure 17 shows a result obtained in April 2017. In August 2018 it looked better: The laser beams both passed the field stop and recombined in F2.

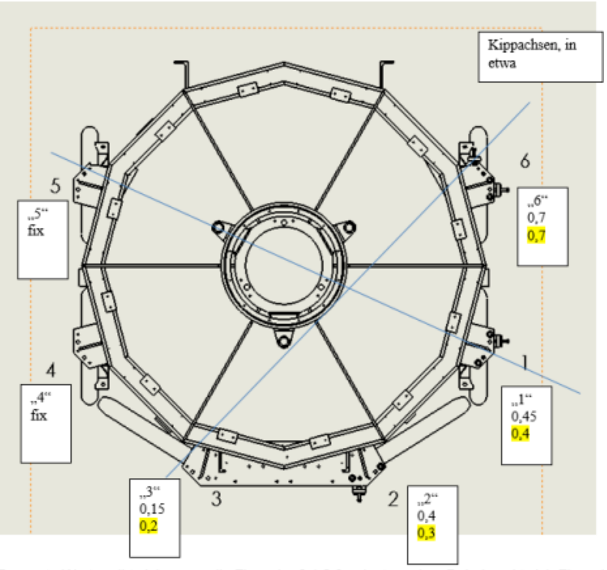


Figure 18 Shimming values for M1. The yellow highlighted values are the actual shimming plate thicknesses. Courtesy Andreas Fischer

Figure 18 shows the shimming plate thicknesses (yellow), which was determined in Feb 2018 and remained also after the recoating in Aug 2018. The positions 1 to 6 are marked on the M1 cell. There is a document written in German by Andreas Fischer containing more details on the mechanical mounting of M1.

This ends the M1 alignment procedure.

Note: As pointed out in Section 4 the optical tolerances are tighter than the mechanical possibilities we have with M1. That means that in the end we have to fine tune by means of the M2 hexapod which means that angles will change and some beam wobble will be introduced.

8 Alignment of M2

The fundamental parameters of M2 are given in Table 3 in Section 11.

Preparations:

- Put a laser in the central position of the laser bar (see Figure 12) and illuminate the F1 field stop (see Figure 14, left panel).
- There is a tiny center mark on M2. Its offset to the mirror vertex is < 0.3 mm
- Shift M2 laterally until the laser hits the center mark.
- Tilt M2 until the laser is in autocollimation

Now M2 is in its nominal position. Table 2 shows the values found in August 2018.

Table 2; M2 position for centered alignment

x	0.5 mm
y	2.0 mm
u	-0.03 deg
v	0.12 deg

9 Alignment of M3

The fundamental parameters of M3 are given in Table 3 in Section 11.

Preparations:

- Put a laser in the central position of the laser bar (see Figure 12) and illuminate M3
- There is a tiny center mark on M3
- Shift M3 laterally until the laser hits the center mark.
- Tilt M3 until the laser is in autocollimation

Note: M3 is much more forgiving than M1 or M2. Especially the lateral shift has much larger tolerances: 2 mm lateral shift decreases the Strehl ratio from 0.96 to 0.81. But a lateral shift has a significant effect on the image position: A lateral shift of 2 mm shifts the image in F4 by 14.6 mm. The corresponding tilt tolerance is 0.05 deg. This means that the autocollimation has to be achieved within 1 mm.

10 Summary

In this document I described how the telescope alignment is done. The typical precision as well as accuracy is 0.2 mm for lateral positions and 0.02 deg for angular position. This is not quite sufficient to reach the ultimate optical performance. To reach the diffraction limit, fine tuning with the M2 hexapod is necessary using some optical feedback like the wave front sensor.

11 Annex: Fundamental Parameters for M1 to M3

The following Table shows the most fundamental parameters for M1 to M3

Table 3: Fundamental mirror parameters

	M1	M2	M3
Substrate diameter	1560 mm	410 mm	360 mm
Footprint diameter for 150 arcsec field	1430 mm (stopped down by shadow tin, not entirely circular)	381 mm	275,4 mm
Radius of curvature	5012.70 mm	1038,79 mm	2797.00 mm
Focal length	2506.35 mm	519.40 mm	1398.5 mm
Effective. f/#	1.75	1.4	5.2
Conic constant	-1 (parabola)	-0.306 (ellipse)	-0.538 (ellipse)
Coating	Al	Al	Al