	NOT Alignment Report **Re-aluminization 2023**	**Date: April 25, 25** **Author: J. Viuho** **Version: 1.0** **Page 1 of 19**

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1. Preface

1.1 Reference Documents

Reference	Document Number	Author	Date	Title
RD 01	DOI: 10.1117/12.134845	Korhonen, Lappalainen & Sillanpää	1991	Hartmann interferometric testing of large mirrors
RD 02	https://www.not.iac.es/telescope/tti/imqual.pdf	Andersen & Sørensen	1996	Report #2: Image quality at the Nordic Optical Telescope
RD 03	https://www.not.iac.es/telescope/tti/dynamics.pdf	Cox	2000	Analysis of the NOT Primary Mirror Dynamics
RD 04	ISBN : 0071363602	Smith	2000	Modern Optical Engineering, 3. Ed.
RD 05		Chrétien	1922	Le Télescope de Newton et Le Télescope Aplanétique
RD 06		Wynne	1968	RITCHEY-CHRÉTIEN Telescopes and Extended Field Systems
RD 07		Jessen	2021	Dismounting and mounting the NOT Mirrors, rev. 2021

1.2 Abbreviations and Acronyms

CCD	Charge-Coupled Device
DIMM	Differential Image Motion Measurement
FWHM	Full Width Half Maximum
LC	Load Cell
LSF	Line Spread Function
LVDT	Linear Variable Differential Transformer
M1	NOT primary mirror
M2	NOT secondary mirror
NIR	Near Infrared
NOT	Nordic Optical Telescope
PC	Photon Counting
PSF	Point Spread Function
RC	Ritchey–Chrétien
RON	Read-Out Noise
TCS	Telescope Control System
WFS	Wave Front Sensor
WHT	William Herschel Telescope

2. Introduction

NOT M1 and M2 were re-aluminized June 5-7th 2023. This document describes the alignment procedure after the aluminization, discusses the odd optical behavior before the aluminization and makes suggestions for future metrology process to allow better collimation.

Originally, the NOT has been required to provide 0.4” spot, and it has been computationally demonstrated that the telescope is able provide a 0.2” FWHM spot if M1 shape is corrected for the low order aberrations **RD01**. Thus, if the telescope is successfully aligned, it can be expected to provide significantly better imaging quality than what has been seen in the recent years. The alignment process was rushed in the 2014 and the outcome resulted in lost reference position of M2. The end product was degraded image quality and bizarre behavior of the telescope PSF. The observed behavior included elongated PSF with varying direction of elongation, with no clear pointing, or time dependence, and varying PSF shape at short time intervals (duration of NOTCam readout each detector quadrant showing different position angle of elongation). The best seeing measured through the telescope optics rarely reached below 1” in any color band, and the telescope was under performing compared to the DIMM stations even in NIR.

The lost M2 reference position and the resulting misalignment has been blamed for the poor image quality, but it seems that more likely explanation is decenter of M1 that would have happened in 2021. If everything else would have been correctly in place, the lost tilt of M2 would have been easy to correct for with TCS. It is also possible that the M1 had already started drifting away from its position during the previous aluminizations.

The M1 centering was measured in a similar way as now in early 2000s, providing a good reference position for the M1. However, the way of measuring the M1 centering prior to aluminization and placing it again “in the same place” approach allows drift of the M1 if not extremely carefully measured. Measuring the M1 centering at the WHT integration hall allows this kind of drift and will be discussed later in this document.

In addition to potential optical and mechanical issues, there are also electronic control system issues which seem to be the main factor driving image quality degradation after the alignment, specifically the focus temperature correction. Active alignment will be discussed in the next section.

3. Active Alignment and Related Issues

The NOT has active alignment correction managed by the Telescope Control System (TCS). The active alignment corrects the M1 shape, the M2 displacement due to sag of the telescope structure, and the focus changes due to thermal expansion of the telescope structure. Under normal operating conditions, these TCS features are not exposed to the observer and the TCS manages the corrections automatically on the background. These corrections are only as good as the sensory input the TCS will be receiving.

By design, the NOT is extremely sensitive to the telescope focus. According to the telescope technical overview on the NOT website, a single focus unit step corresponds to 0.35µm motion of M2, which results to 15.2µm move of the telescope focal plane. To say in another way, the movement of M2 results in 40 larger movement of focal plane. The issue has been discussed in **RD02** along the temperature dependence of the telescope focus. In order to tackle the problem, a large number of temperature sensors was installed in late 90’s or early 00’ which were fitted to the telescope structure, the M1, and the dome. In addition to the focus temperature correction these sensors were used for monitoring mirror and dome seeing.

Over the years, majority of these sensors have one-by-one failed, and they have not been replaced. Currently, the focus correction relies on few functioning sensors which are not optimally placed. Finding a proper telescope structure temperature is complicated task since there are always temperature gradients present in the structure. For example, during the day time, the air in the dome is stratifies cooler air lowering down and warm air raising closer to the ceiling. During night time, the top of the telescope structure is exposed more to the sky, causing a larger radiative heat loss on the side facing the sky compared to the side facing the observing floor.

All the temperature changes can be experienced as thermal expansion differences in the telescope structure. Consequently, the temperature map of the telescope structure is very complicated, varies in time, and has a delayed pointing dependency making single point temperature measurement insufficient to give a reasonable understanding of the structure temperature. Additionally, using single sensors for measuring the structure temperature risks the reference temperature being affected by temperature changes driven by heated air from control electronics. Without proper temperature correction, it is not possible to maintain the telescope in focus even when aligned. However, if the telescope is correctly aligned, PSF in the off-focus images will appear round instead of elongated as is the case with offset mirror(s).

In addition to the focus temperature correction, the M2 tilt should be temperature corrected, based on temperature difference between the struts on the side facing the sky and the sky facing the dome floor. However, the telescope image quality is significantly less sensitive to the M2 tilt than to the telescope focus.

The M1 shaping depends on the assumption that the M1 is resting free on top of the load cells. That requires that the lateral counterweight arms are properly aligned to provide correct force and direction of the force at different altitudes. If the forces are not correct, M1 aberrations may be observed which may have unexpected altitude dependencies.

The M1 has also been found to be oscillating with relatively high frequencies **RD03**. During long exposures the M1 oscillation may cause image blur and mishaping the PSF if the oscillation has a preferred direction. The possible sources include M1 bellows themselves, wind, instrument rotator, telescope/building drives, cooling fans, etc **RD03**. The contribution of M1 oscillation to the image degradation might be small, but it has potential for explaining the short term PSF variation, especially, in presence of astigmatism due to offset mirrors making focus changes strongly visible.

Additionally, telescope tracking may contribute to the image quality degradation.

4. NOT Design

4.1 Optical Design

The NOT is a Ritchey–Chrétien (RC) telescope and by design is aplanatic; the two hyperbolic mirrors cancel out each other's to coma and spherical aberration terms. However, the usable field-of-view (FoV) of RC designs are limited by astigmatism and field curvature. By design, the NOT is required to reach 0.4" FWHM and it has been computationally demonstrated that 0.2" should be reachable, if the M1 shape is corrected for coma, spherical aberration, astigmatism, triangular coma and quadratic astigmatism. Historically, sub 0.4" stars have been observed and the telescope can be expected to provide very good image quality if well aligned.

There are two options for having on-axis astigmatism in a RC design; offset M2 or misshaped M1. If M2 is offset from the optical axis, the image of the zero field angle will also move away from the optical axis (telescope "looks" sideways). If M2 is far enough from the optical axis, one may observe astigmatism when in focus even at the detector center.

See **RD04, RD05** and **RD06** for further reference on RC design.

4.2 Mechanical Design

The telescope stands on an alt-az fork with. The primary mirror is mounted on a mirror cell that is hanging from the center section of the telescope structure. The M1 cell doubles up as a M1 transportation vehicle. Consequently, when primary is removed from the telescope for re-aluminisation, the mechanical alignment of the between the center section and mirror cell, as well as, between the mirror cell and instrument adapter will be lost. The mirror cell is pinned to the center section, and the adapter to the mirror cell with conical pins in order to allow accurate repositioning after aluminisation.

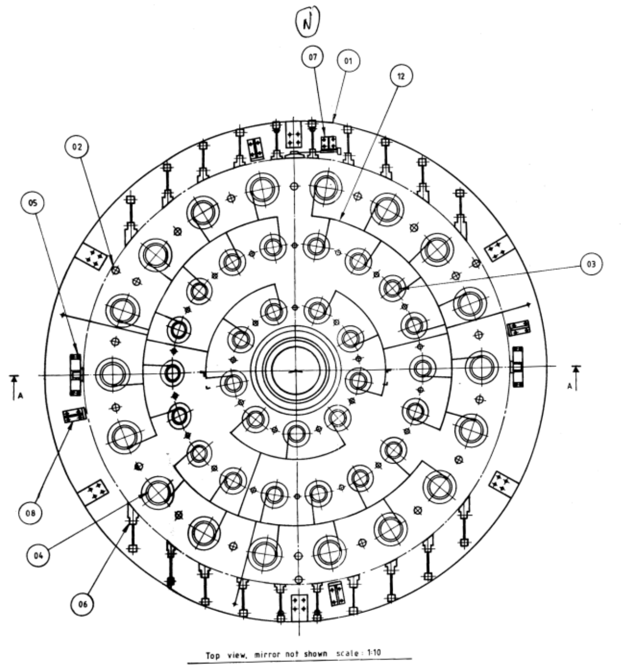

Figure 1: M1 cell structure. The East side lateral fix point is marked as 05, the West side can be found symmetrically on the opposite side of the cell, and the transverse fix point is labeled as 07.

In this document, terms lateral and transverse are used to refer N-S and W-E -axis in the dome coordinate system. Telescope drawings follow the same coordinate convention for the fixpoints, apart from the counterweight arms supporting M1 on N-S -axis are named as “transverse supports” instead of “lateral supports”. These will be referred as “lateral supports” in this document.

The M1 is position is fixed by three load cells (LC) from below, and from three fixed points on the rim of M1. Additionally, there are 45 air bellows supporting the M1 from below, and 20 lateral support arms maintaining the shape of the mirror when pointed down. The 45 bellows are divided in three sections with 15 bellows for each LC.

The lateral fixed points lock the rotation and N-S translation. W-E translation is only locked by the transverse fixed point on the North side of the M1 leaving the M1 partially rotationally unconstrained. In principle, the M1 mounting will allow low-amplitude pendulum like motion around the North side transverse fix point. This is a potential explanation why the M1 seems to hunt more for its position in W-E direction than N-S (see appendix for measurements).

TODO M1 on bellows, eigenfrequency and mode. Conical pin tolerances. Derived mechanical tolerances from optical tolerances.

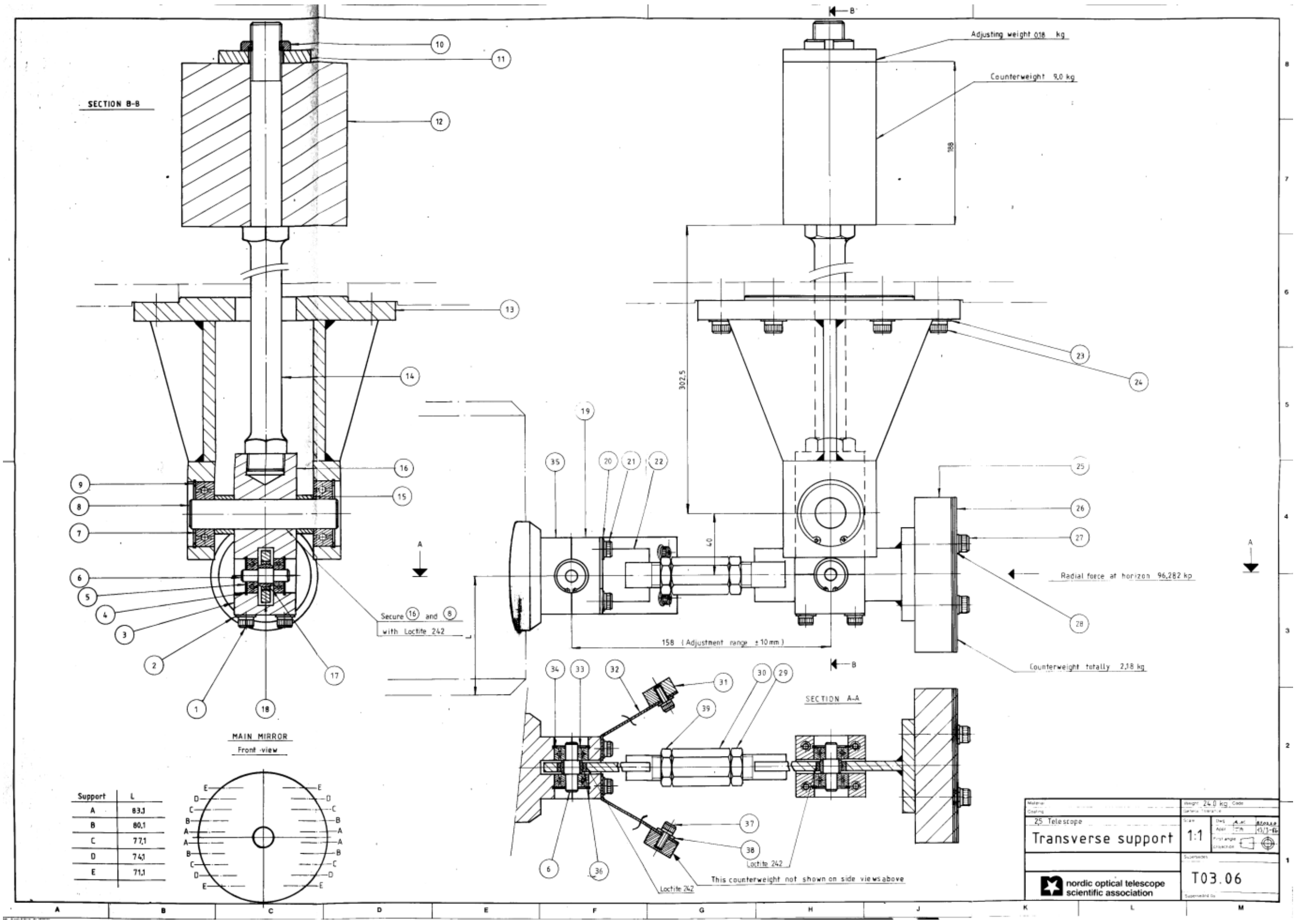

Figure 2: Mechanical drawing of lateral support arm. The distance between the two pivots (6) on the two push rods (22) has been adjusted such that the counterweights (12) are standing rigth above the pivoting point of the assembly (8), the counterweight rods (14) passing through the holes in the support (13) right in the middle.

5. Alignment

The typical NOT alignment process consists of reproducing the centering of M1 and M2 by measuring them back to the same position as they have been prior to the aluminization. No optical analysis is done prior pointing on the sky. Once on the sky, in an off-focused image the shadow of the central obscuration is found concentric with the outer rim of the off-focus donut and finally M2 tilt is adjusted for the smallest FHWM. Refer **RD07** for the standard procedure.

5.1 Optical Alignment with Pupil Imager

Since early 2000's, the rotator axis has been chosen as the definition for the telescope optical axis. The M1 central hole and the stop have been machined with a tool mounted on the instrument rotator making the apertures concentric with the rotator axis. The rotator is mechanically referenced with alignment pins to the M1 mirror cell, and the M1 mirror cell is referenced in similar way to the telescope central section. A pupil imager can be used for finding M2 centering and tilt. A pupil imager has been used for the M2 alignment in early 2000's, 2021 and 2023. The alignment process with the pupil

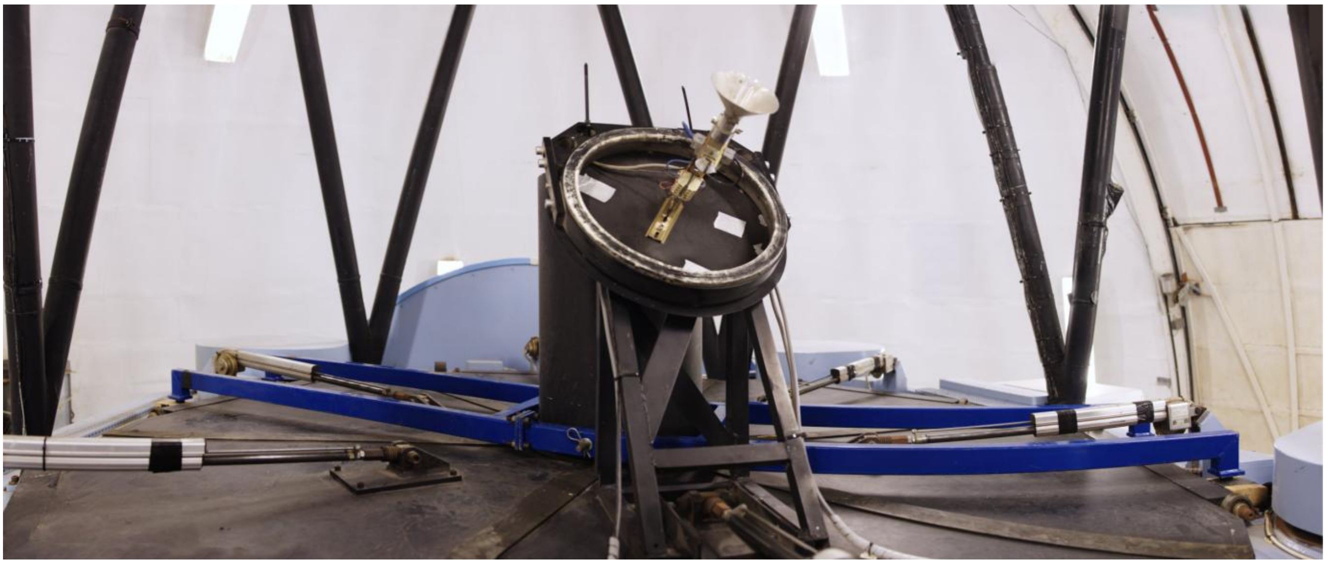

Figure 3: The M1 baffle support preventing the baffle from falling down when center section is removed. It needs to be removed to allow mirror covers to open.

imager is very straightforward, provides excellent optical alignment by direct measurement and can be done during daytime.

Step-by-step guide:

1. Remove M2 baffle so that the the M2 rim can be seen with high contrast.
2. Mount pupil imager lens #1 in ALFOSC aperture wheel, and pupile lens #2 in the grism wheel.
3. Focus ALFOSC such that the image is focused on the rim of M2.
4. Image the M2 with rotator positions -90°, 0°, 90°, and 180°
5. Find the pixel coordinates of M2 center in each image and find the radius of pupil image motion.
6. Calculate image scale based on the physical diameter of M2 (510mm) and do required correction. Vertical travel range of top unit is 1.6mm, so small vertical adjustments can be made easily with the displacement mechanism. Larger vertical adjustments and all horizontal adjustments have to be made by moving the spider.
7. Once M2 is centered, focus the pupil imager or on M1 stop (aperture ring ~50mm above the M1).
8. Image the telescope stop with rotator positions -90°, 0°, 90°, and 180.
9. Adjust M2 tilt to remove pupil image motion. Since the M2 is now concentric with the rotator, the observed image motion will be due to M2 tilt (the stop is viewed via M2).

It might be necessary to move the pupil lens #2 in its holder to be able to focus on M2 and M1 stop. The lens is mounted on a threaded barrel which is locked with a retainer ring. The lens can be moved by screwing it in the thread.

5.2 2023 Alignment – Mechanical alignment

After mirrors were loaded on the transport truck, the M1 baffle was removed. First, the baffle was lifted up with the same scissor table that had been used for removing bottom section of the sky baffle. This was done in order to allow to put weight on the mirror covers which are rest on the M1 baffle. As a part of the standard procedure, the M1 baffle is left hanging on the top of the center section, and one is not allowed to place extra weight on the mirror covers. Once baffle was was supported from below the support structure could be removed, and mirror covers opened. From this point, the mirror covers had to stay open until the baffle is mounted back since they are rested on the M1 baffle. If M2 will be worked on under these circumstance, extra care should be taken not to leave loose items on the top unit since they would fall directly on the M1. All but one the six rubber pads preventing the M1 from falling forward were removed from the center section. This was done to allow the T-bar to move freely. The pad in the proximity of LC2 was left in place for safety.

All lateral support arm swivel arms and ball bearings were cleaned with WD-40 and exercised to make sure that all of them were able to move freely. Lateral supports 11, 12, 19 and 20 were the dirtiest, and also the stiffest. After cleaning all swivel arms were moving freely and the ball bearings seemed to be still in good condition. Excess oil was removed and the arms were mounted back in their place when the mirrors arrived back to the telescopes.

Figure 4: Roughing pump connected bellow o1b1.

Once the mirrors and instrument adapter were mounted back following the normal procedure, a dedicated adapter plate was installed on the rotator and telescope was pointed to the lock-pin position. The T-bar is centred on the adapter plate with its own smaller diameter plate. To persons climbed inside the center section. First, a pre-assembled wooden jig was installed, see Figure 5. The jig was used for resting the weight of the T-bar while it was inserted in. The T-bar weights ~35-40kg and requires two persons to lift it. A third person was assisting through the adapter standing on a ladder, by lifting T-bar from the threaded mounting rod. Ideally, a round or square profile bar would be inserted around the rod to make lifting easier for the person standing on the ladder. Once the T-bar was through, it was immediately secured with its bolt and small lid on the adapter plate while the two persons standing in the center section were holding it. Afterwards, the telescope was pointed to zenith and the T-bar was slightly loosened to allow moving it. Centering was done by measuring the radial distance between the T-bar mounting rod respective to the screw holes on the adapter plate. Once centered, the T-bar was tightened again. The final uncertainty on the T-bar centering is probably less than 100µm. The T-bar center was measured along several different axis to the reading limit of a caliber.

The screw hole patterns on the T-bar should have been measured before inserting it. They were assumed to be symmetric, but that was found out not to be true when it was time to install the sensor. Some time was spend making an aluminum adapter block for lowering the LVDT at correct height and mate with the T-bar screw holes. With the proper spacer in place, the LVDT was fitted with 25mm long screws reaching about 5mm below the camfer on the M1 rim (see Figure 6). The centering was measured and the results are presented Section 8.2. Initially, the M1 was found out to be 1.7mm off center mostly towards North.

After the first measurement, the transverse fixed point on the North side of M1 was released. The M1 was not locked in place by the transport pads, and the result was an unintentional slide towards South by 3mm. Slide towards South was due to the load cells being tilted slightly towards South. Right after, the transport pads were brought into contact with M1 and the mirror was pushed closer to the center while continuously measuring with the Mitutoyo micrometer tool. The M1 was found back to its approximate center, and it was measured again with the T-bar. The M1 was now found almost perfectly centered on the NS-axis, but was off by 2mm on the EW-axis. An EW correction was done and the centering was found out to be almost perfect being about 50µm off center. The transport pads were tightened, the opposite sides tightened simultaneously by same amount, and the mirror was lowered down.

M1 position was measured with the Mitutoyo micrometer tool both before and after lowering the mirror. 70µm shift was observed in NS direction and 120µm in EW. This was considered to be sufficient centering, and in order to release extra tension from the mirror supports. After the mirrors was lowered down, the N side fixed point was released, seated again, and tightened. The lateral support arm lengths were adjusted. The lateral supports furthest out, both towards E and W, were the ones that needed to be adjusted the most (1, 2, 9, 10, 11, 12, 19, 20). Counterweight arms 19 and 20 were the worst since the arms were almost touching rim of their holes in the center section. Curiously enough, it seemed that both N and S side lateral supports were pushed outwards. One would have expected them to be pushed outwards on one side and inwards on the other due to translation of the M1. Unfortunately, the lateral support positions were not noted down before the aluminization so that the two could have been compared.

After the lateral support arms were adjusted, and before lifting the mirror up, each and every of the 45 bellows were sucked down and released again in order to make sure that the force they provide is directed normal to the mirror blank. This was done by connecting a vacuum turbo pump's roughing pump to the pneumatic line of each bellow one-by-one. The pneumatic control line to bellows can be accessed in the boxes on the side of the center section, there is one for each load cell section, see Figure 4. It takes about a second to bring a single bellow down and in total the process is quite quick. The process should be done while the mirror regulation is turned off.

Next, the mirror was clamped in place with the transport pads, and the lateral fixed points on W and E side were released and tightened again. The centering was checked with the micrometer and negligible motion was measured. These values were adopted as the new reference for M1 centering, and the Mitutoyo micrometer references measurements at each transport pad are presented in Table 1. These values should be use reference until further notice. See the full list of measurements in the Section 8.

Table 1: Mitutoyo micrometer reference values at each transport pad location.

N	6.05
E	5.27
S	5.70
W	6.39

After releasing the stress from fixed points and lateral supports, and removing mechanical contact from the bellows, all the forces acting on the M1 should act towards their assumed direction. The fixed points and lateral supports were possibly forcing a slight rotation on the M1 and the lateral supports were pushing the N and S side of the M1 slightly down, essentially, producing slight astigmatism. See Section 5.3 for further discussion.

It seemed that the M1 centering precision after repeated lifting up – lowering down cycles had precision of ±25µm on N-S -axis and ±50µm on E-W -axis. The M1 motion can be controlled at level of ~20µm if the rubber sheets on the transport pads are compressed against the mirror. Then probably the main uncertainty will be the surface roughness on the M1 rim.

Once the centering was completed, the tilt measurement began. The telescope was pointed to the lock-pin position and the LVDT sensor's tip was replaced with a 90° tilting head with a ball bearing roller on it. Ideally, this measurement should be done with two LVDTs at the opposite ends of the T-bar to cancel out the tilt of the bar itself. However, only one working LVDT+cable set was available. Additionally, the last security rubber pad would have limited the measurement with two LVDTs to a half a rotation would not have been practical. The LVDT was placed such that the ball bearing was rolling right under the stop ring giving a measurement circle with *r=1.245m*. The height of M1 surface was measured above each load cell to make the tilt adjustment easier. Initially, LC2 was found out significantly higher than the two other load cells which as expected since LC2 was lifted significantly in 2021 after the M2 movement. The M1 tilt can be calculated from trigonometry by the help of Figure 8 and load cell height difference in Table 4. After correction the M1 was level to +/-30µm corresponding to few arcseconds in tilt, the measurement accuracy limited by the T-bar itself.

Figure 5: T-bar coming out of the telescope after contact measurement of M1 with a help of a wooden jig on which it can be rested.

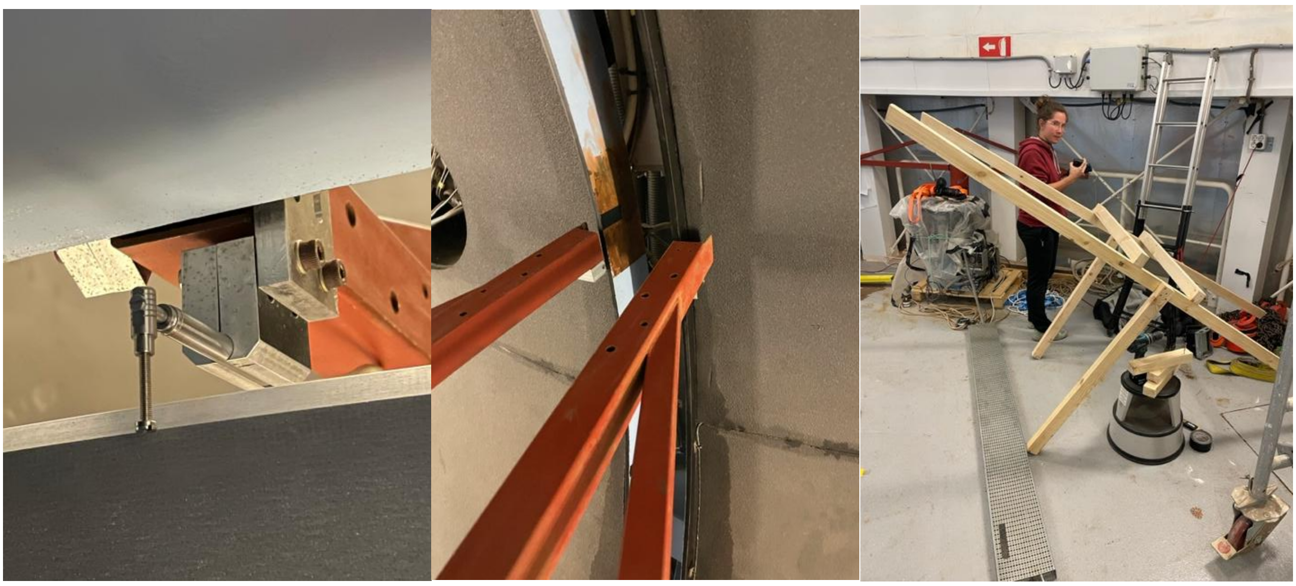

Figure 6:(left) LVDS probe running on the outer rim of M1. (middle) T-bar inserted in its location. Extra extension prevents it from falling on the mirror. The threaded screw hole placement is somewhat random, measure carefully in advance. (right) Wooden jig to help inserting T-bar and M1 baffle. The three T-bar guiding pieces have been removed to allow use with M1 baffle.

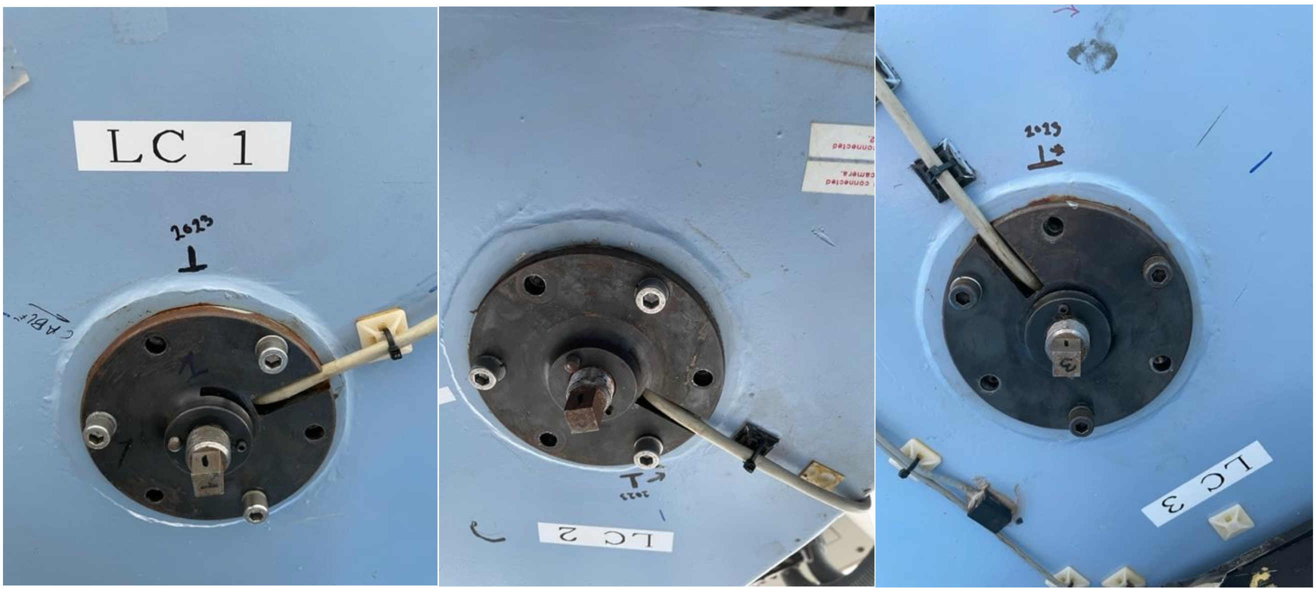

Figure 7: Photographs of each load cell as adjusted and marked in 2023. The T-bar measured LC heights are marked with the upside-down T-symbols on the mirror cell. Radial line indicates the direction normal to the marked face of the adjustment screw. For example, LC1 is as measured with the T-bar, and LC2 close to 180° rotation towards the direction indicated by arrow.

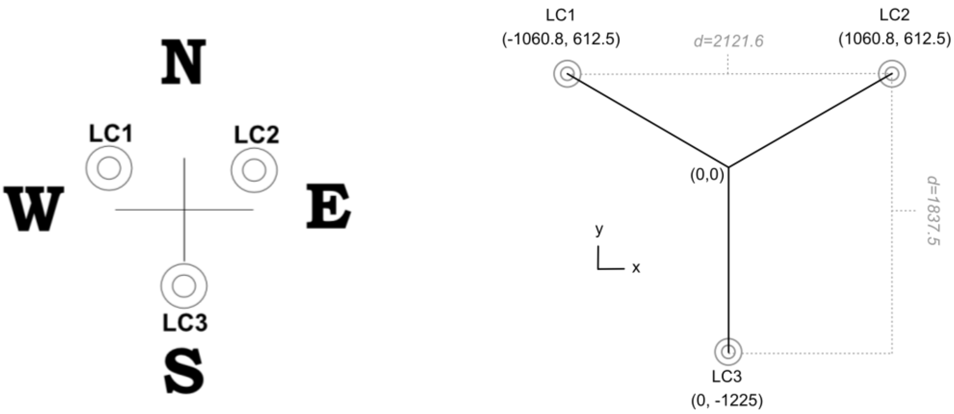

Figure 8: Coordinate reference, cardinal directions in the dome coordinate system (left), and load cell position in Cartesian coordinates with origin at the M1 center (right). In both cases the M1 is viewed from above.

5.3 2023 Alignment – Optical Alignment

The M2 centering was found by installing the pupil imager lenses to ALFOSC and imaging the M2 with rotator positions -90°, 0°, 90° and 180°. Since the rotator axis has been chosen as the definition of the optical axis, the M2 offset from the optical axis can be measured as its image motion. The M2 was found out to be off by 1.9mm in the displacement direction and -0.8mm sideways. In 2021, both axis were with 0.25mm. This was difficult to understand since it is not possible to move the top unit by such a large amount in the spider. The required offset was large enough to require external help and it was decided not to attempt it. Additionally, it was possible that the actual explanation was that the rotator axis would be pointing to a different direction which should be investigated before the M2 is moved. It was decided to proceed with the on-sky alignment despite the M2 being off-axis.

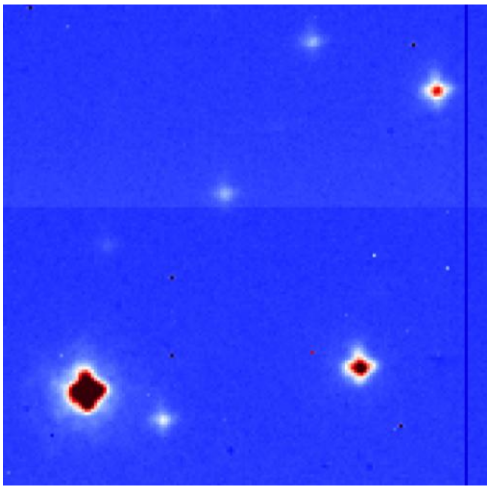

Figure 9: NOTCam HR camera image of over-correction of astigmatism before re-shaping of M1. The overcorrection is probably due to the adjustment of lateral support counterweights. Before adjustment the M1 bellows were working against the counterweights. After adjustment, the mirror is resting free.

During the first nights in operation it was found out that there were larger than normal rotator tracking errors. During the M1 measurements it was also noticed that a certain fraction of the rotator turn had higher friction. Later on it was found out that a piece of wire had been clamped between the mirror cell and rotator causing this. Either the rotator or mirror cell would need to be tilted by 1.6’ to produce the observed offset. This would correspond to 0.7mm height change at the radius of mirror cell mounting pads, or 0.2mm at the radius where the rotator is mounted. This needs to be investigated further and the discussion will be added to the next version of this document. **TODO.**

M2 tilt was not adjusted with the pupil imager since the method was found out to be not so accurate in 2021. The correct tilt was expected to be very close to the pre-aluminization value. The remaining optical alignment had to be done on sky. After pupil imaging the baffles were installed back. M2 baffle was installed normally, and five people were lifting M1 baffle. M1 baffle was inserted by using the same wooden jig as was used with the T-bar. Two threaded rods were installed on the M1 baffle to help to guide it in correct orientation and fasten it in its place before mounting its own bolts. The M1 was secured with two nuts, and then the remaining positions were bolted normally. Finally, the threaded rods were removed, and the last two bolts installed.

The first night after completion of mechanical alignment was lost due to high humidity, and the optical alignment was started only during the second night. First, the on-axis coma was minimized by centering the central obscuration in an off-focus image. Off-focus images were taken with ALFOSC. The telescope was pointed to Arcturus soon after sunset and 1s off-focus images were taken through Hα filter. There was a little bit off hunting around the best M1 tilt. Concentricity was determined by eye which was somewhat subjective. This was done visually with DS9. Nevertheless, the final tilt was rather close to the one measured with T-bar, and a very small correction was applied in the end (See Figure 7).

After the on-axis coma corrections, in focus images were checked. They were decent but elongated. The M2 tilts were tried on both axis, but it seemed that the M2 orientation was close to correct. The images were looking reasonable and since there was no clear plan on the M1 shaping, the telescope was handed over to the observer and 2/3 off the night was observed normally. The following night NOTCam was installed and seeing happened to excellent. The M1 aberrations became visible and strong astigmatism was observed, see Figure 9. This was found out to be due to non-correct astigmatism compensation by the active optics. Before the aluminization, the TCS astigmatism correction had amplitude of 800nm and angle of 10°. The M1 shape was corrected by changing the astigmatism correction angle to 90° and amplitude to 900nm. Essentially, the pre-alignment correction was lifting N and S sides of the mirror rim, and the post-alignment correction the E and W sides of the M1. The change in the astigmatism term is most likely due to adjustment of the lateral supports.

Before, the lateral supports were slightly pushing the mirror down and TCS was compensating for it, whereas, afterwards the M1 was resting freely requiring a lift from the sides not supported by the counterweight arms. This is a potential cause for unexpected M1 behavior as function of altitude, and it would be interesting to study if the M1 behaves similarly as before or not. Given that the M1 better supported, it might be finally possible to include higher order Zernike terms in the active M1 correction, and possibly have altitude look up tables. However, wind and temperature dependencies should still be studied.

After M1 astigmatism angle was adjusted, the image quality started to look good. 0.3”-0.4” images were recorded in K-band with NOTCam HR camera. The telescope PSF was still mishaped, but the FWHM was below the detector sampling limit with NOTCam WF camera and ALFOSC. It was not clear if the M1 shape would be stable in long term and it was decided to leave the telescope like this. The M1 shape could be perfected at a later date with more proper software analysis capabilities. Telescope PSF seen through NOTCam HR camera is shown in Figure 10.

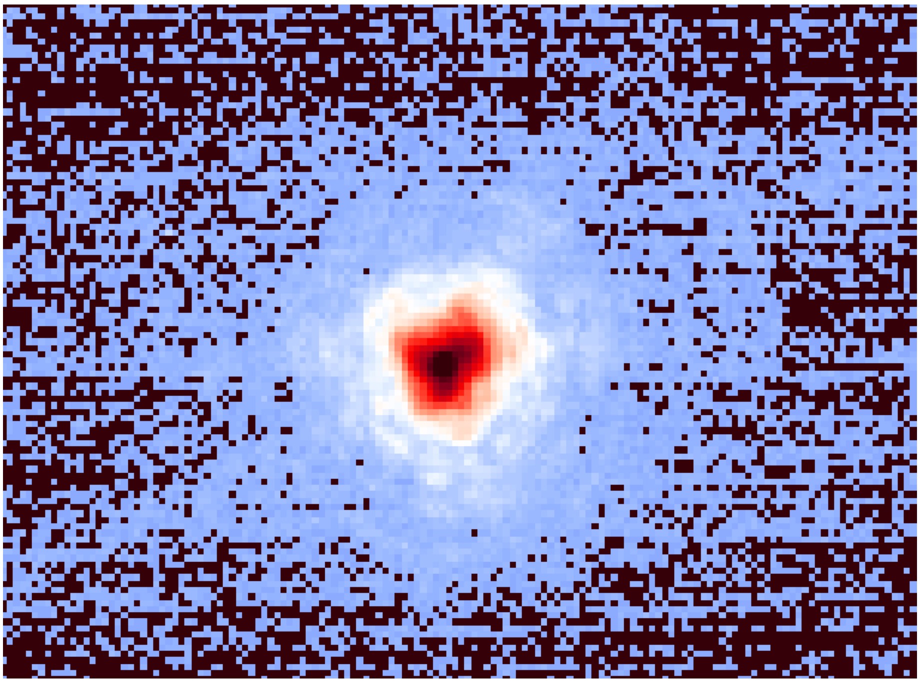

Figure 10: Chara imaged with NOTCam HR camera through 2122nm NB filter. Pixel scale 0.078”/pix and measured FWHM of 0.32”. Clear aberrations are still present.

6. Suggestions for Future

The measurement geometry in combination to haste imposes a significant risk of not reproducing the M1 position in its cell. The centering measurement should be carried out with a sufficient time, tooling and methodology. The floor of the integration hall at the WHT is slanted towards a drainage almost right under the area where the M1 is placed in its cell. The floor slanted in four different direction. In theory, it should be possible to find wheels of the mirror cell only on two of these slanted surfaces and level it. However, that would probably require moving the mirror cell side ways making the operation practically impossible, or at least extremely time consuming.

Due to the slanted floor, the M1 is lowered into inclined mirror cell. Normally, the rotation is adjusted first for which the setup might be even sufficient. Once the rotation is considered to be correct, the lifting triangle is rotationally locked, and the centering begins. The M1 is measured while hanging in air and lowered slowly while measuring. However, due to the skew mirror cell which acts as the reference, the measured centering will depend on the height of the mirror above cell, as well as the surface roughness on the measurement point making the centering measurement a try-and-luck exercise. Only way to measure properly would be to lower the M1 to rest fully on the mirror cell, and then lift fully up again to translate it. This might be achievable, but maybe not practical.

Suggested change to the procedure would be to place the M1 in its cell only measuring the rotation and approximate centering at the WHT. If the space between telescope center section and mirror cell allows inserting the tools used for rotation, it would be also better to adjust the rotation in dome after mirror cell has been mounted back. The centering measurement should take place in the dome after M1 and mirror cell have been mounted back. The M1 should be lifted up by bellows, and centered by pushing it with the transport pads. Movement can be controlled with level of ~20-30µm while the pads are in contact with M1 and slightly compressed. All measurements should be carried out while the mirror is lifted, and the reference values from this document should be used for all future aluminizations. Measuring the centering on the day mirror is removed as a reference value allows over-the-time drift of the M1. Even under the best measuring conditions this approach would potentially result in 100µm shift in a single aluminization just due to the M1 oscillating around its average position.

Measuring the centering with the Mitutoyo micrometer has quite large uncertainty because of the surface roughness of the mirror rim. The peak-to-valley roughness of the M1 rim might be order 100-200µm. The measured distance at each transport pad is thus dependent on the M1 rotation and height. The size of the micrometer ball tip might average out the roughness somewhat, but the measurement is most likely still affected by the surface roughness. The measurement surfaces should be polished in order to make the centering procedure easier and more reproducible.

During the future aluminizations, all extra tension should removed from the M1 supports. Any non-desired force will deform the mirror in a non-predictable and non-controllable way. The process can be similar to what has been described in this document. Once the centering has been found, the M1 should be lowered down by guiding with the transport pads. Once the M1 is down, the lateral support arms and fixed points can be mounted back. Once the fixed points and lateral support arms are in place, the M1 can be lifted up and its centering checked. If the M1 found to be in its place within measurement errors, the lateral support should be adjusted if needed. However, that should be only the case if M1 rotation or centering has not been reproduced. The centering measurement of the counterweight arms may not be really quantitative but is an indicator if the operation has been successful or not.

It was found out that the M1 reproduces its position within ±25µm on NS-axis, and ±50µm on WE-axis between consecutive lift up-down-up cycles. This might be a real measurement or an artefact caused by the surface roughness. Nevertheless, the practical centering accuracy limit with the current equipment is about ±50µm. The M1 should be positioned within 100µm or better after each aluminization.

7. Summary

The M1 centering was contact measured with a T-bar fitted a LVDT-sensor. The M1 was found 1.6mm off the center when measured with the T-bar, and it was strongly tilted away from LC2. The tilt had been introduced in 2021 when the M2 was moved with the spider and was expected, but the 1.6mm offset is too large to be explained by drift over the previous aluminizations, given that the M1 has been centered correctly in early 2000's. Probable explanation is that the M1 was not centered in 2014 and was the actual main cause of the observed imaging errors instead of the lost M2 reference.

Initially, the M2 was found 1.9mm off on the altitude axis, and -0.8mm offset horizontally. These offsets were too large to be explained by misplacement of the secondary unit and more likely explanation is that the optical axis had changed. To see the M2 2mm off center would require 1.6' tilt on the rotator. This would correspond to a 0.7mm height difference in the mirror cell mounting, or 0.2mm at the rotator. It was found out that wires were clamped between the rotator and the mirror cell making. The M2 position should be measured again with the pupil imager to see if the axis has changed.

If it will be found out that the rotator axis has changed indeed, all the measurements have been affected by it. A correction term has to be calculated. By initial calculations without detailed dimensions the M1 centering correction might be in range 100-400µm making it significant. Astigmatism can be still seen when off-focus which might indicate that this is the case.

When in focus, the telescope provides 0.4" FWHM spot with some remaining M1 aberrations when pointed at high altitude. ALFOSC and NOTCam WF will be limited by their pixel sampling, and an eye should be kept on under sampling under good seeing conditions. The telescope image quality is limited by the ability to keep it in focus. Several new temperature sensor has to be installed on the telescope structure in order to allow better temperature focus correction. This will be required even after the final collimation of the telescope. If the M1 and M2 are concentric, no on-axis astigmatism will be observed, but the telescope focus will be still sensitive.

8. Measurements

8.1 Mitutoyo Micrometer – Centering Measurements

The values in the table below have been measured with the Mitutoyo micrometer with a long probe arm, through the holes in the M1 transport pads. The method is the standard M1 centering measurement for re-aluminization. There are a number of considerations to take into account when measuring with the tool. The tool can be slightly tilted in the hole resulting to a measurable difference. Also, the M1 sides have surface roughness of some 100µm, and this should be kept in mind while measuring. Consequently, there is a significant difference in taking the measurements depending on if the M1 is lifted up or not.

Table 2: Mitutoyo micrometer centering measurements.

Measurement	N	E	S	W	Comment
(10/06/2023) #1	5.25	6.85	6.63	5.8	The same as t-bar #1?
(10/06/2023) #2	3.28	5.95	8.54	5.8	The same as t-bar #2?
(10/06/2023) #3	6.069	5.484	5.811	6.276	After t-bar measurement
(10/06/2023) #4	5.95	5.22	5.85	6.5	The same as T-bar #5. Take the following Mitutoyo differences and refer to T-bar centering measurement #5.
(10/06/2023) #5	6.02	n/a	5.79	6.37	All values before are mirror lifted. This is M1 lowered after the measurement #4. After measurement #4 mirror was lifted up again.
(10/06/2023) #6	6.05	5.27	5.7	6.39	Fixtures mounted, final centering.
(11/06/2023) #7	6.01	5.37	5.6	6.3	Telescope pointed to horizon and up to zenith again several times since the previous measurement.

8.2 T-bar – Centering Measurements

Readings for the T-bar M1 centering measurement were taken above each transport pad location making it easy to apply offsets to M1 position. The M1 rim was touched with a screw mounted on the LVDT probe five times at each location and mean of the measurements was taken. The screw was touching roughly 5mm below the camfer on the M1 rim (see **Error! Reference source not found.**). The LVDT probe had a little play on it, and especially if the travel is short, it can be pushed in slightly skew affecting the measurement. There was no attempt to characterize this behaviour and its effect, and simply several measurements were taken. The LVDT has its zero point at the mid-point of the physical travel range. The LVDT maximum travel range is from +1.976mm to -1.976mm, positive maximum being fully extended and negative maximum fully pushed in. In case of the centering measurement, higher number means being further away radially from the rotation center.

The measurements are in units of millimeter in the table below.

Table 3: T-bar centering measurements.

Measurement	N	E	S	W	dNS	dEW	Comment
(10/06/2023) #1	0.299	-1.761	-1.361	0.971			
	0.295	-1.754	-1.357	0.987			
	0.301	-1.749	-1.356	0.982			
	0.301	-1.753	-1.361	0.981			
	0.296	-1.744	-1.359	0.978			
Average #1	0.2984	-1.7522	-1.3588	0.9798	1.6572	-2.732	
(10/06/2023) #2	-1.311	-1.019	0.287	0.126			
	-1.306	-1.036	0.294	0.137			
	-1.298	-1.028	0.309	0.135			
	-1.273	-1.028	0.292	0.132			
	-1.304	-0.952	0.293	0.134			
Average #2	-1.2984	-1.0126	0.295	0.1328	-1.5934	-1.1454	
(10/06/2023) #3	-0.391	-1.477	-0.552	0.638			
	-0.414	-1.487	-0.554	0.637			
	-0.42	-1.5	-0.552	0.604			
	-0.398	-1.473	-0.541	0.64			
	-0.496	-1.485	-0.513	0.647			
Average #3	-0.4238	-1.4844	-0.5424	0.6332	0.1186	-2.1176	
(10/06/2023) #4	-0.454	-0.653	-0.5	-0.312			
	-0.471	-0.622	-0.514	-0.298			
	-0.462	-0.653	-0.533	-0.265			
	-0.491	-0.699	-0.525	-0.274			
	-0.483	-0.642	-0.518	-0.288			
Average #4	-0.4722	-0.6538	-0.518	-0.2874	0.0458	-0.3664	

(10/06/2023) #5	-0.436	-0.384	-0.515	-0.504			Before #5 M1 was lowered down, all bellows were sucked down before the mirror was lifted up.
	-0.455	-0.399	-0.525	-0.503			
	-0.441	-0.45	-0.534	-0.503			
	-0.431	-0.439	-0.524	-0.489			
	-0.443	-0.461	-0.499	-0.485			
Average #5	-0.4412	-0.4266	-0.5194	-0.4968	0.0782	0.0702	

8.3 T-bar – Tilt Measurements

In case of the tilt measurement, the LVDT probe was fitted with a 90° angled mounting piece with a ball bearing. The LVDT was mounted on the T-bar such that the ball bearing was running right at the radius of the stop ring giving a rolling radius of *r=1.245m*. In case of the tilt measurement, more negative the number the higher up the measurement point is.

The measurements are in units of millimeter in the table below. LC stands for Load Cell.

Table 4: T-bar height above load cell measurements.

Measurement	LC1	LC2	LC3	Comments
#1	-0.376	-1.926	-0.784	
#2	-0.65	-0.654	-0.664	
#3	-0.664	-0.726	-0.73	
#4	-0.684	-0.705		
#5	-0.67	-0.703	-0.73	