Combined MASS/DIMM instrument for atmospheric turbulence measurements. Optical and mechanical design. Alignment.

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Introduction

This document describes the optical and mechanical design of a low-resolution turbulence profiler (MASS) combined with the DIMM device in a single instrument, according with a Proposal to CTIO [1]. The project was implemented in frame of the AURA contract No. C10389A. The electronics of the device and detailes related to it are presented in a separate document [6]. Also, separate documents contain Turbina Software reference guide, Turbina user guide [11], and Supervisor user guide [7], which complete the full description of the MASS/DIMM instrument and its control software.

The MASS/DIMM optical scheme was specially calculated for the use with two feeding telescopes: standard 10-inch Meade and 35 cm telescope for the TMT (Thirty Meter Telescope) DIMM custom-made by the German company Halfmann.

The principles of the work of MASS and DIMM components of the combined instrument are described in [4], [2], and [8]. Meanwhile, according to the experience obtained in a year-long exploitation of the original MASS device [5], some changes have been introduced in the geometry of the main optical component of MASS – pupil segmentation unit.

The Chapter 1 of the document presents the final optical parameters of elements together with the tolerances for the critical measures. In addition, the tables give the full specifications for the optical elements, both for the standard ones for purchasing in commercial companies and the special elements manufactured by the contractor.

The Chapter 2 describes the general mechanical design of the instrument. The dimensions are given for both the Meade- and TMT-fed devices which differ in types of CCD camera used and in the construction of the mechanical interfaces for attachment of the instrument to the feeding telescope.

The next chapter is a guide for alignment of the optical scheme elements – the operation which is mandatory after the device assembly or while installing the device on the telescope. Exit pupil optics tuning (MASS segmentator and DIMM mirrors), focusing and lateral positioning of the Fabry lens, checking the entrance pupil position are the subjects of particular attention.

Lastly, the Chapter 4 helps to compute the principal parameters of the device resulted from the finished alignment procedure. This is critical for correct interpretation of the scintillation data which is performed by the MASS and DIMM software. Appendices which follow give technical parameters of the optical and mechanical device components.

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Chapter 1

Optics design

1.1 Basic principles

We shortly remind here the principles of a Multiaperture scintillation sensor (MASS) instrument. MASS measures four scintillation indices in small central circular aperture and 3 concentric annular aperture as well as 6 differential scintillation indices for all possible pairwise aperture combinations. Scintillation indices produced by a turbulent layer at some altitude h depend the turbulence intensity, on the aperture geometry and on the spectral range (so called weighting function $W(h)$ [4, 5, 9]).

Using these 10 measured values, a calculation of some integral characteristics of the atmospheric turbulence and a restoration of turbulence vertical profile with low-resolution (5 – 6 fixed layers) are possible. All the weighting functions drop to zero at zero altitude.

DIMM (Differential image motion monitor) measures fluctuations of the angular distance between two images produced by two circular apertures about 8 – 10 cm diameter separated by about 20 cm. Theory states that the rms image motion is proportional to the turbulence integral over full atmosphere. So, the weighting function for DIMM is un-depending on altitude.

The idea to combine two different turbulence measuring devices in one, grew from the facts, that:

- Multiaperture scintillation sensor (MASS) doesn't sense a turbulence located in boundary layer (first 1 km above ground). Possible solution — a generalized mode of MASS measurement, was tested with original MASS device. It was found, that this method will be able give a reasonable results with large aperture feeding telescope only. On the other hand, DIMM measures both low and high turbulence.
- When a Cassegrain-type small telescope is used to feed DIMM device, only two circular parts of entrance pupil (about 15% of area) are used. MASS device uses even less part of entrance pupil. But original MASS set of entrance apertures (with 13 cm largest aperture) requires 40 cm or larger Cassegrain telescope.
- Numerical simulations show [5] that reducing the largest MASS annular entrance aperture (the segment D) down to 8.5cm optimizes the method sensitivity for middle altitudes. This means that a non-expensive (amateur class) telescope with diameter 25 – 30 cm can be used to feed the MASS device.

The following general solution was chosen and implemented in combined MASS/DIMM instrument for turbulence measurements:

- to re-image the plane of entrance pupil of feeding telescope to the exit pupil plane;
- to separate sub-apertures in that plane, one for the MASS channel and two for the DIMM;
- for the MASS sub-device, to split the light with the help of a segmentator unit (see [2]) onto four MASS channels, and to re-image the exit pupil at a photocathodes of MASS detectors;
- for the DIMM sub-device, to re-image the star in the plane of the CCD detector, while simultaneously moving apart the images produced by each of two DIMM sub-apertures.

The following Sections describe this process in detail.

1.2 Principal geometry of MASS/DIMM device

The MASS/DIMM device was designed and calculated for usage with two different feeding telescopes: a standard 10-inch Meade amateur telescope (Cassegrain-Schmidt optical system) and a 35 cm telescope for the TMT (Thirty Meter Telescope) DIMM custom-made by the German company Halfmann. For the calculation of the design parameters, the data listed in the Table 1.1 were used.

Table 1.1: The telescope parameters adopted for MASS/DIMM optical design. All dimensions are in millimeters

Parameter	TMT telescope	Meade 10″ telescope
Nominal equivalent focal length F_0	2800	2500
Focal length of primary mirror F_1	875	570
Diameter of primary mirror D_1	350	254
Telescope focal plane position Δ_0 behind primary	200	200
Magnification on secondary mirror m	3.2	4.4
Focal length of secondary mirror F_2	-372	-185
Separation of primary mirror from secondary one d_{12}	619	427
Central obscuration parameter q	0.292	0.251
Diameter of secondary mirror D_2	102	64

1.2.1 Entrance and exit pupils. System magnification

To make an image of the entrance pupil, a Fabry lens with some focal length F_{abry} must be placed on optical axis of the instrument. In this case exit pupil will be located at a distance af (according to Fig. 1.1) from the lens. Really, the Fabry lens re-builds not original entrance pupil, but its image produced sequentially by primary and secondary mirrors of a telescope. The

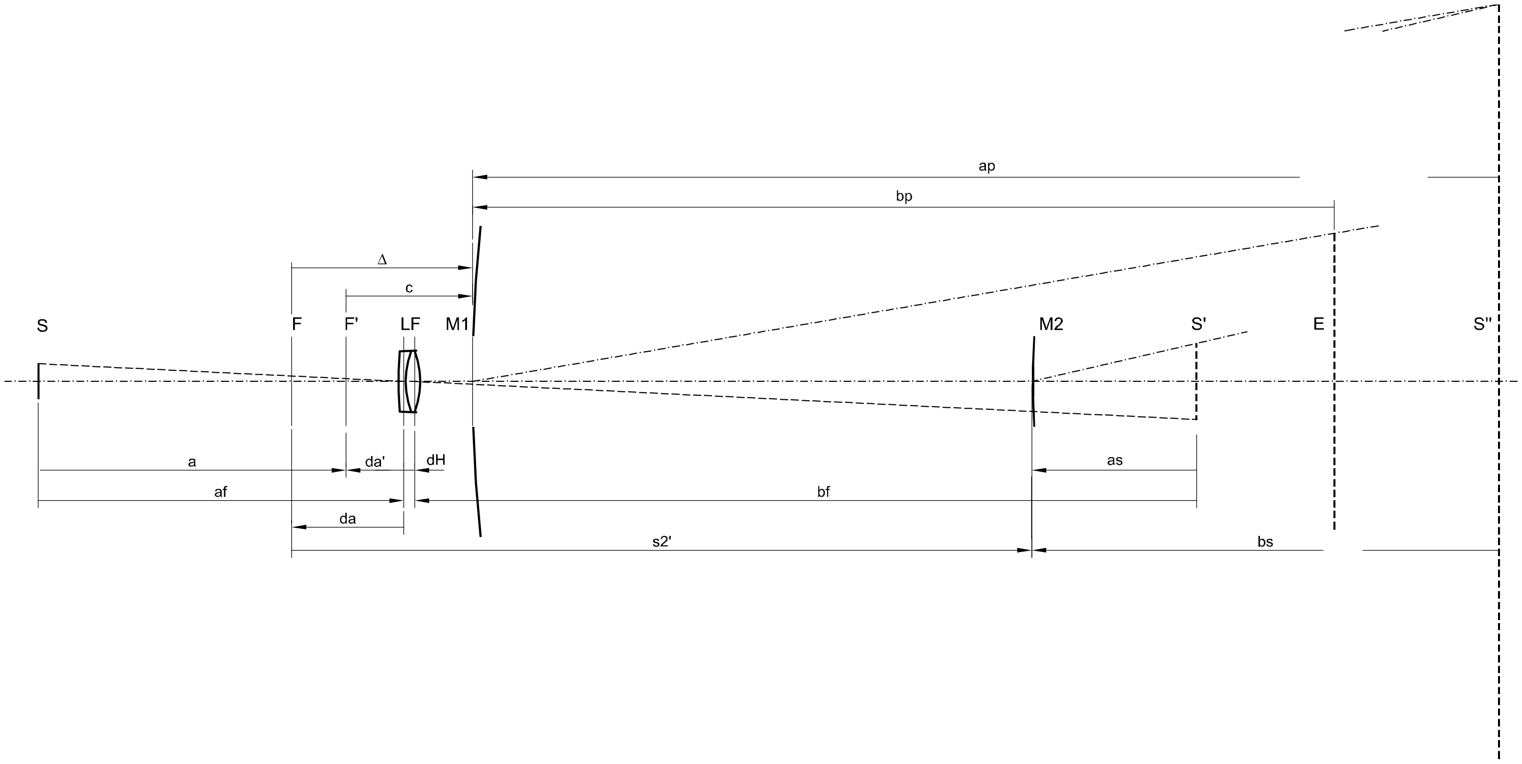

Figure 1.1: Principal optical layout used for calculation. S — pupil segmentation unit, F — telescope focal plane, F' — Fabry lens+telescope focal plane, LF — Fabry lens, M1 — pole of the primary mirror, M2 — pole of the secondary mirror, S' — image of S produced by Fabry lens, S″— image of S' built by mirror M2, E — entrance pupil of the system, which is the image of S″produced by primary mirror. All values designed by right arrow are positive, otherwise — negative. *dH* — distance between principal points of Fabry lens. Other values are explained in Section 1.4.

dimension and location of this image depend on the exact geometry of telescope, and change slowly when telescope is refocused.

Physically, the position of the exit pupil is fixed, and the location of the entrance pupil plane are defined by the telescope system as well as by the Fabry lens focal length and position. The entrance pupil location isn't important for the results of measurements. Since the elements splitting light between channels are placed in the exit plane and work as aperture stop, the working entrance pupils for both MASS and DIMM sub-devices, can be defined in reverse light path as the images of these pupil stops produced by the Fabry lens + telescope optical system.

The ratio of the diameter of an aperture in the entrance pupil plane to the diameter of respective physical element placed in the exit plane, is the magnification K of the instrument. It depends on telescope and device geometry as well.

For the design, the location of the entrance pupil plane was chosen to be 100 mm in front of the secondary mirror (at top edge of telescope tube). It is common for Cassegrain-Schmidt system, but not for pure Cassegrain. Such position is very convenient for instrument check and alignment.

The nominal value of $K = 15.00$ was chosen ($K \approx 20$ in the original MASS). To provide both the adopted entrance plane location and the needed system magnification, the Fabry lens focal length and its position with respect to exit plane must be chosen correctly for both telescopes. The exact value of system magnification influences final results of both MASS and DIMM because the geometry of entrance pupil is used in computation turbulence intensity from directly measured values.

1.2.2 Fabry lens

The optical layout of the MASS/DIMM instrument (without feeding telescope) is presented in Fig. 1.2. The coordinate system which is used here and further, is as follows:

- Z-axis along optical axis of the instrument
- Y-axis lies in plane of symmetry of the instrument towards viewer.
- X-axis is perpendicular to both Z- and Y-axes.

In order to diminish overall dimensions of the device, the Fabry lens LF is placed before the focal plane of the telescope. In this case the Fabry lens shifts the focal plane to a new position FP where we have a real image of a target star. In this plane the field aperture FA is placed. Additionally, such LF placement protects the interior optics of the device from dust.

Such design requires re-focusing the telescope each time the Fabry lens is shifted along the axis. The possibility to move Fabry lens along optical axis is necessary in order to adjustment the system magnification, which can differ from its nominal value due to lens focal length tolerance and uncertainties in telescope geometry.

In the Table 1.2 the main optical parameters of the MASS/DIMM device are listed. Catalogs of Melles Griot and Edmund Optics companies were used to select the Fabry lens. The exact formulae for computations are presented in [10].

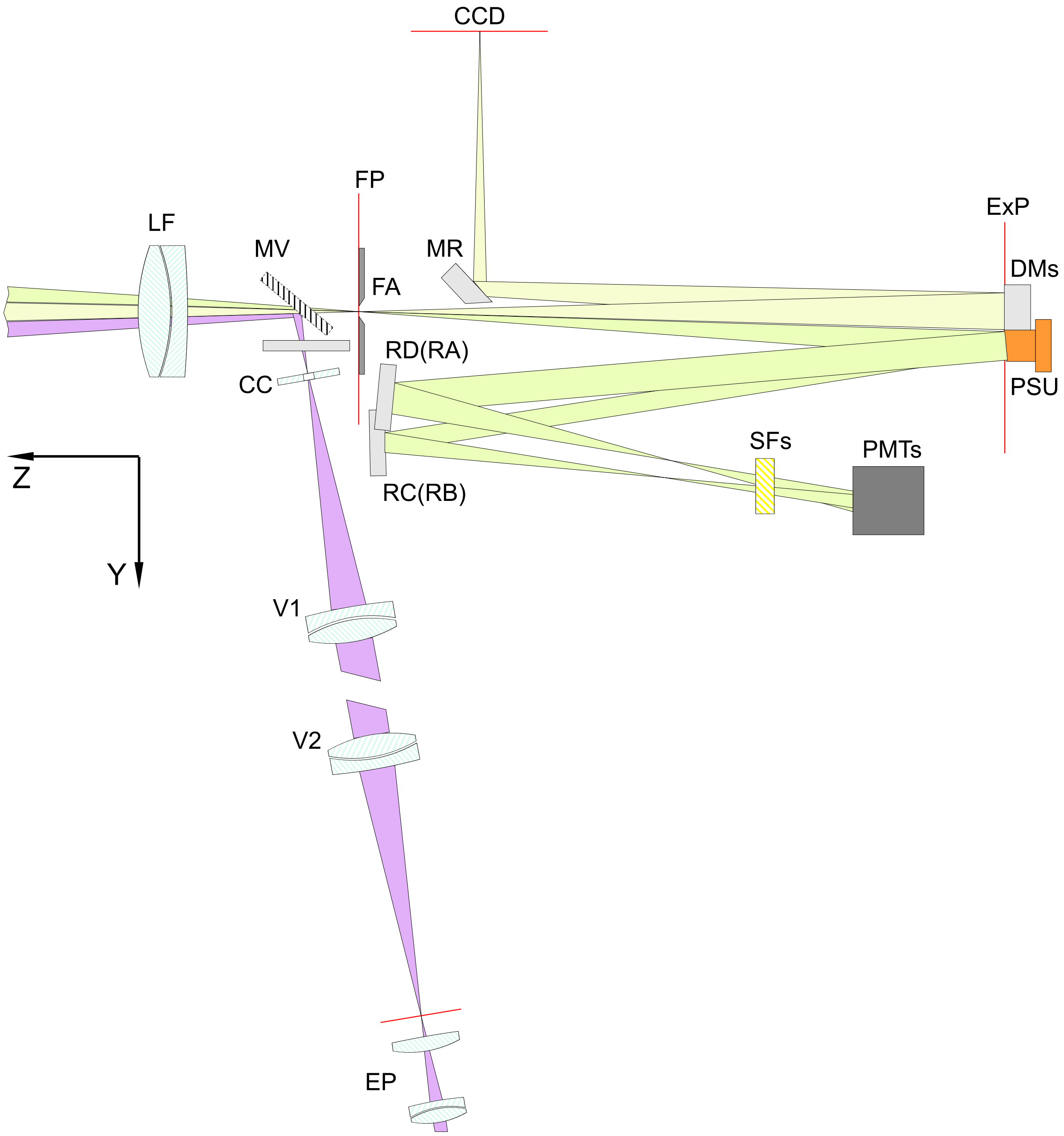

Figure 1.2: Optical layout of MASS/DIMM device in ZY plane. Common parts: LF — Fabry lens, FP — instrument focal plane, FA — field aperture, ExP — plane of exit pupil. MASS sub-device: PSU — pupil segmentation unit, RA, RB, RC, RD — re-imaging mirrors, SFs — spectral filters, PMTs — MASS detectors. DIMM sub-device: DMs — two DIMM re-imaging mirrors, MR — folding mirror, CCD - plane of CCD detector. Viewer: MV — viewer removable mirror, CC – glass plate with central hole, V1, V2 — transmoving objective, EP — eye-piece.

Table 1.2: The MASS/DIMM main optical parameters. All dimensions are in millimeters

MASS/DIMM parameter	for TMT telescope	for Meade telescope
Fabry lens focal length F_{abry}	140	125
Fabry lens diameter D_{abry}	25	25
Distance between FP and EP planes a	123	123
LF position with respect focal plane da'	-38.7	-28.7
Instrument magnification K	15.52	14.50
Entrance pupil plane position b_E	-100	-100
Scale in the focal plane $scale_F$	$108''$/mm	$115''$/mm

1.2.3 Geometry of exit pupil

The size of full exit pupil imaged by Fabry lens depends on magnification as well as on the entrance aperture of telescope. The table below lists some characteristics of the pupil geometry for both feeding telescopes. The drawing of exit pupil is shown in Fig. 1.3 for both feeding telescope. The further light separation (segmentation) between four channels of MASS sub-device and two channels of DIMM sub-device is produced with help of MASS pupil segmentation unit (PSU) and two spherical mirrors DM1 and DM2. Evidently, these elements must be within the exit pupil. To provide these lateral shifts of the exit pupil are foreseen in the design (see Sect. 2.2).

Table 1.3: Telescope exit pupil geometry. All values are in millimeters

Pupil dimension	TMT telescope	Meade $10''$
Inner diameter	7.1	6.5
Outer diameter	22.6	17.5
Clear segment width	7.7	5.5

These data force to adopt the maximal outer diameter of the MASS pupil segmentation unit as 5.5 mm and maximal diameter of DIMM aperture for the case of Meade telescope as 5.5 mm, too. For the case of TMT telescope, there is more freedom to select size and position of the DIMM apertures inside exit pupil, but the telescope secondary mirror spider must not cause any vignetting of either PSU or DIMM apertures.

1.3 MASS optics

The optical scheme of the MASS sub-device is shown in Fig. 1.2 as ZY plane view, and in Fig. 1.4 as ZX plane view (from viewer side). The main optical element of the MASS sub-device is the pupil segmentation unit (PSU). PSU forms four reflected beams and reflects them in different directions.

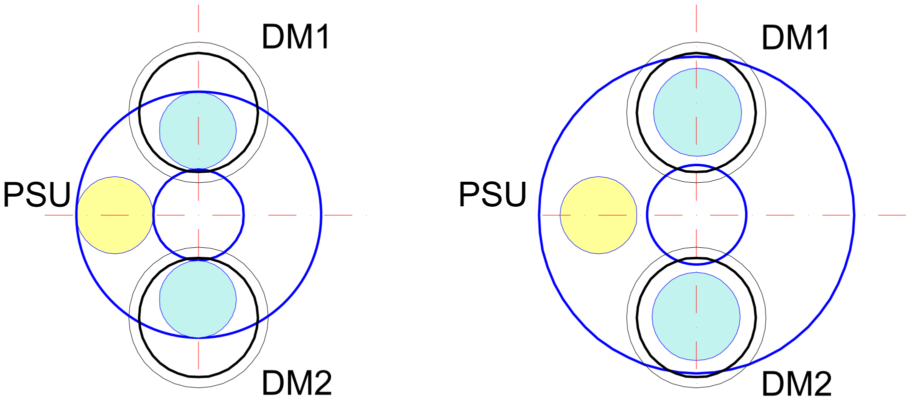

Figure 1.3: Geometry of exit pupil for two feeding telescopes. Left — Meade telescope. Right — TMT feeding telescope. PSU is shown by yellow. DIMM masks are shown by cyan. Black — the placement of DIMM re-imaging mirrors.

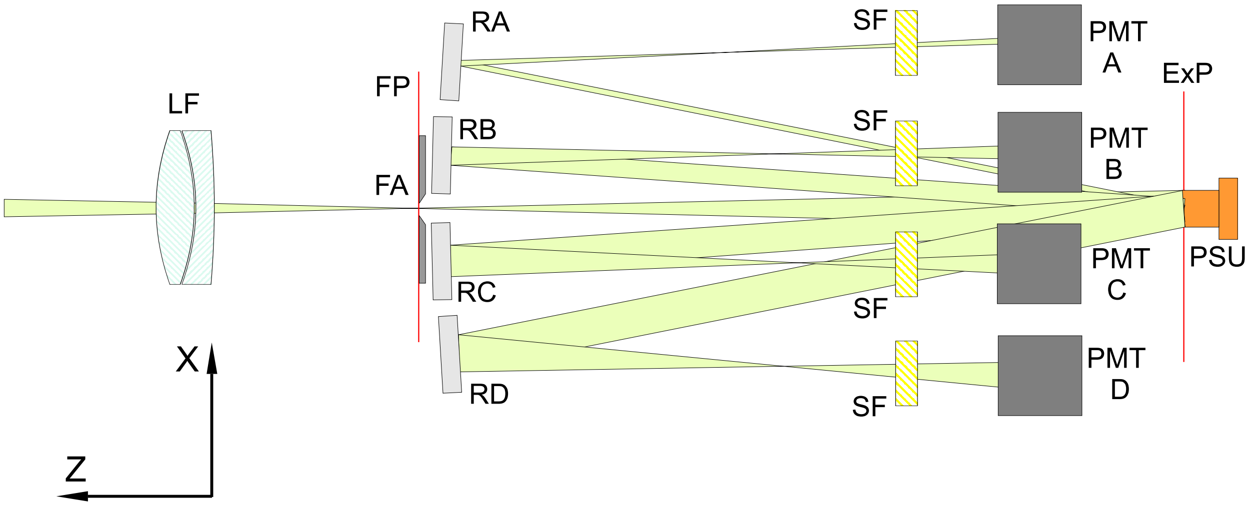

Figure 1.4: Optical layout of the MASS sub-device in ZX plane (corresponds to the bottom view in Fig 1.2). DIMM sub-device and viewer are not shown. Common part: LF — Fabry lens, FP — instrument focal plane, FA — field aperture, ExP — plane of exit pupil. MASS: PSU — pupil segmentation unit, RA, RB, RC, RD — re-imaging mirrors of the A-, B-, C-, and D-channels, SF — four spectral filters, PMT — four detectors.

1.3.1 Pupil segmentation unit

The PSU is located off the instrument optical axis (see Fig. 1.3 and Fig. 1.4) at distance of 6.5 mm for both feeding telescopes, to avoid the central obscuration in the exit pupil. This requires to align the exit pupil by shifting the Fabry lens in Y direction by ±0.5 mm. This is done during Fabry lens alignment.

To provide the light reflection from the PSU segments in needed directions to the re-imaging mirrors RA, RB, RC, and RD, the segment mirrors are produced tilted by 8.0° to the PSU rotation axis. Then, the segments of the PSU are rotated around PSU axis so that the rotation angle between the adjacent segments equals 30° . In order to compensate partially for the large segments tilt and to place the re-imaging mirrors closer to the instrument optical axis, the PSU as a whole is inclined by 4.75° around X axis. Note that the incident beam is inclined by -2.8° with respect to the instrument axis, too.

Angles between the segment normals and incident/reflected beam are 6.9° for outer channels A,D and 6.4° for inner channels B,C. Segments have concave surface with a curvature radius of 250 mm that ensures non-divergent beams after the reflection from segmentator. This permits to use small re-imaging mirrors. Despite the segments tilt, their projections are circular with high accuracy.

Using the optimal set of MASS apertures [5] and geometry of exit pupil (see Table 1.3) the dimensions of the PSU segments were chosen as listed in Table 1.4.

Table 1.4: PSU segment dimensions and entrance segment dimensions for both feeding telescopes. All values are in millimeters

Segment/ Channel	Physical diameter	TMT telescope	Meade telescope
Segment D outer	5.50	85.4	79.8
Segment D inner	3.90	60.5	56.6
Segment C outer	3.85	59.8	55.8
Segment C inner	2.20	34.1	31.9
Segment B outer	2.15	33.4	31.2
Segment B inner	1.30	20.2	18.8
Segment A outer	1.27	19.7	18.4

The PSU is fabricated from hard bronze, its mirrors are polished as a whole with optical quality. The reflecting coating is made by evaporation under vacuum and consists of 3 layers: a Chromium layer deposited on the bronze, an Aluminum layer, and a protective SiO overcoating. The microphotograph of the PSU is shown in Fig. 1.5. Final diameters of PSU segments, measured with the help of such microphotographies for all produced segmentator, agree well with the nominal diameters of Table 1.4.

1.3.2 MASS channels A, B, C, and D

MASS Pupil segmentation unit produces four reflected beams. Each beam falls on the corresponding re-imaging spherical mirror RA, RB, RC, and RD.

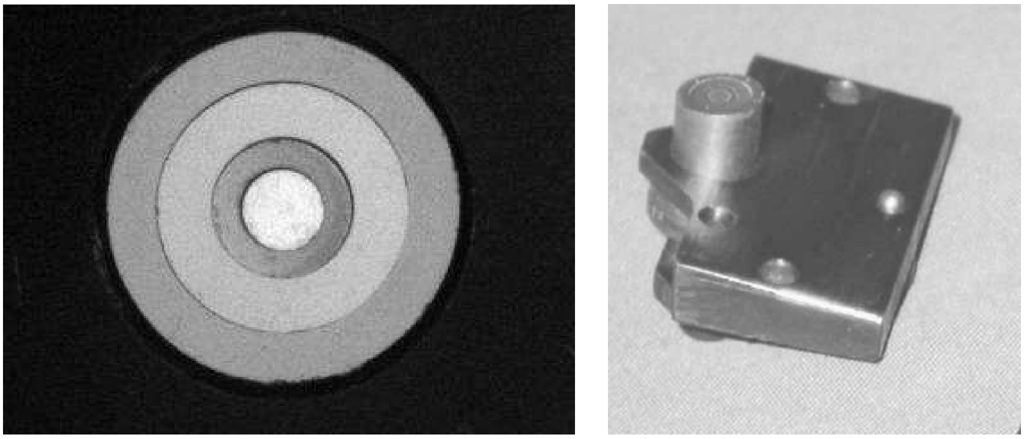

Figure 1.5: On the left: Top view of one of the MASS segmentator, illuminated by scattered light. On the right: Segmentator mounted in its holder.

MASS re-imaging mirrors are chosen to be the same as in original MASS, i.e. 12.5 mm diameter and 51 mm focal length. The distances from the PSU to mirrors are equal to 120 mm for all mirrors, the distances from mirrors to corresponding PMTs are 88.7 mm. The angles between the mirror normals and incident/reflected beams are 11.1° for outer channels A,D and 8.3° for inner channels B,C. Usage of simple spherical mirrors under such angles produces significant astigmatism.

Re-imaging mirrors are tilted slightly to direct light to PMT photocathodes. The outer mirrors are symmetrically tilted by 4.5° around Y-axis and by $-3.9°$ around X-axis. The inner mirrors — by 1.9° and 1.0° , respectively. The resulting tilt of the outer mirrors (normal to Z-axis angle) is 5.96° . The normal projection onto the XY plane has a position angle $\pm 131°$ with the axis Y. For the inner mirrors, this angle is 2.19° while their position angle is $\pm 62°$. Re-imaging mirrors are coated by multi-layer dielectric film, reflecting up to 99% in the blue-green region of the spectrum.

Light falls onto photocathodes under relatively large angles (13° to 15°), contributing to the distortion of PSU segment images. The effect of star motion into field aperture was estimated, and no significant energy re-distribution at photo-cathodes was found. The size of the segment images on the photocathodes is reduced by 0.73, so the largest image (D segment) has diameter about 4.0 mm.

The glass spectral filters FS are placed between the re-imaging mirrors and the PMT photocathodes. The filters define the short-wave cutoff of the MASS spectral response. Additionally, the filters close the holes in MASS/DIMM box lead to PMTs, thus protecting the instrument from dust.

1.3.3 MASS spectral response

Compact photomultipliers R7400P from Hamamatsu are used as light detectors. These PMTs have bi-alkali photocathode of 7 mm diameter. The spectral sensitivity is typical of bi-alkali photocathodes.

The spectral response of MASS is shaped by the PMT spectral sensitivity, the transmittance of the spectral filters SF and the reflectance of the re-imaging mirrors. The final spectral response

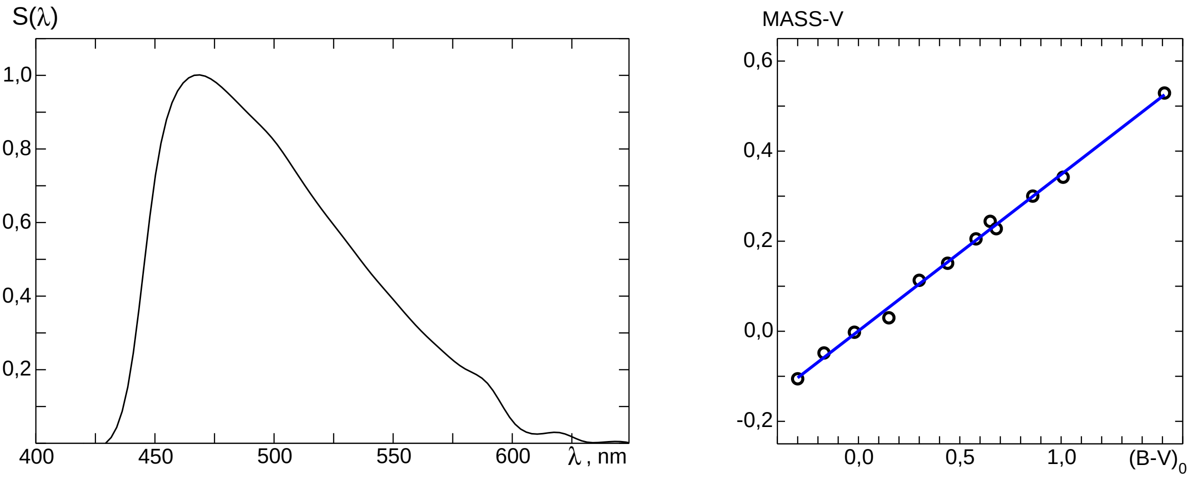

Figure 1.6: On left: Spectral response of the MASS device. On right: Color equation between MASS magnitude and star color index B-V.

is shown in Fig. 1.6 and numerical data are presented in the Table 1.5. Such spectral response produces a dependence of MASS magnitude on star color. In Fig. 1.6 (right) the dependence is plotted. Transformation from standard V magnitude is described as follows:

$$MASS = V + 0.347(B - V)$$

Table 1.5: MASS spectral response in relative photon units. Wavelengths in nanometers

λ	$S(\lambda)$	λ	$S(\lambda)$	λ	$S(\lambda)$
420	0.000	500	0.823	580	0.203
430	0.004	510	0.729	590	0.160
440	0.206	520	0.636	600	0.061
450	0.720	530	0.552	610	0.025
460	0.963	540	0.467	620	0.029
470	1.000	550	0.391	630	0.005
480	0.956	560	0.317	640	0.004
490	0.891	570	0.255	650	0.000

The integral parameters of the MASS spectral response are: effective wavelength for A0 star 496 nm, effective spectral bandwidth about 85 nm.

1.4 DIMM sub-device

Two spherical mirrors DM1 and DM2 covered by two-aperture mask are placed in the exit pupil. These mirrors transfer the stellar image from the instrument focal plane to two images on the

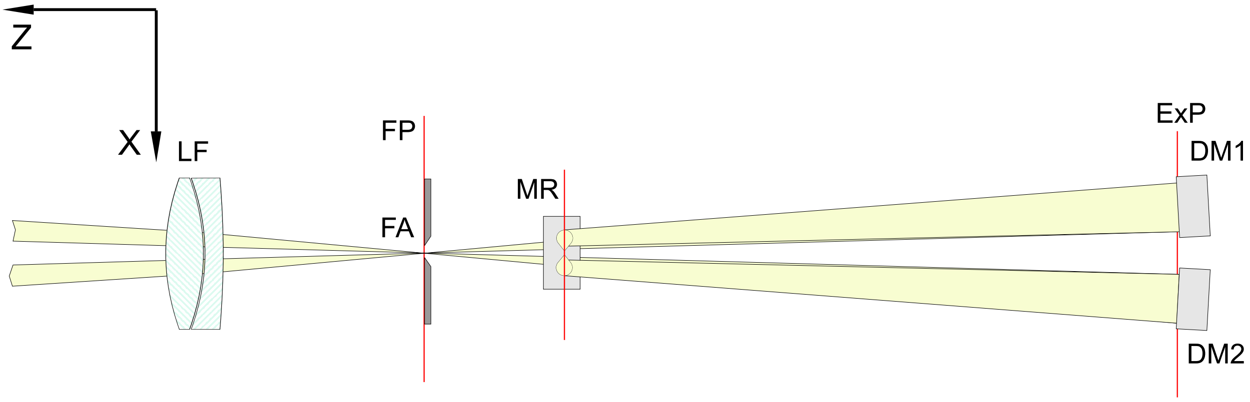

Figure 1.7: Optical layout of DIMM sub-device in ZX plane (corresponds to the top view in Fig 1.2). The MASS sub-device and viewer are not shown. Common part: LF — Fabry lens, FP — instrument focal plane, FA — field aperture, ExP — plane of exit pupil and mask. DIMM: DM1 and DM2 — DIMM re-imaging mirrors, MR — folding mirror, CCD — plane of CCD detector.

CCD detector surface. The distance between the mask holes defines the DIMM base (see Fig. 1.2 and Fig. 1.7).

The diameter of re-imaging mirror is equal to 10.8 mm with clear diameter 9.8 mm (see Fig. 1.3). Such a diameter permits to select the DIMM base with the help of the DIMM mask only. The distance between mirror centers is 15.0 mm. The focal length of such a mirror must be 67.5 ± 1 mm to provide minimal aberrations and the needed distance to CCD. During the alignment of the DIMM sub-device we found that focal length probably is 1 mm less than nominal.

The mirrors are made very thick for their size — 5 mm, in order to provide a stability of the image. The mirrors are coated by Aluminum with protective SiO film.

The main characteristics of the DIMM sub-device are presented in the Table 1.6.

Table 1.6: DIMM sub-device characteristics for both feeding telescopes. All values are in millimeters

Segment/Channel	TMT telescope	Meade telescope
Physical diameter of aperture	6.4	5.5
Diameter of entrance aperture	100	80
Physical DIMM base	15.5	12.0
Entrance DIMM base	230	170
Scale on CCD	$88 \pm 3''$/mm	$93 \pm 3''$/mm

The distance between the DIMM mirrors and the folding mirror MR is 100 mm. Fig. 1.7 is drawn for the case of TMT feeding telescope, where the beam cross-sections are maximal. In this case the reflected beam cross-sections at the MR mirror are equal to 2.5 mm and the distance between them is about 5 mm. The minimal tilt of the DIMM mirrors is 1.25° in YZ plane, which produces a clearance of about 0.5 mm between the incident beam and the edge of MR for the worst case of star position in the field aperture (shift 0.7 mm to the CCD edge). At the mirror surface, the clear space from the edge is about 0.8 mm in this case. The incident angle varies from 0.95° to 1.55° depending on the star position in the aperture, and this can changes the abberations as well. In the plane XZ, the DIMM mirrors are tilted by ±3.19° . That these angles must be adjustable very finely to provide the needed distance between two star images. Re-imaging produces an additional scale change with magnification about 1.2.

1.5 Field aperture and viewer

A field aperture is located in the focal plane of the instrument. It serves to limit the contribution of sky background to the light measured by MASS detectors. The aperture also limits the field of view DIMM sub-device: for this reason, a compromise size of the field aperture as large as 2.2 mm ($4'$) was chosen. The aperture is made as a hole in a flat thin steel plate.

The size of a wide field of view for star finding is defined by the viewer design and is about 9 mm or $16'$. To view this field, a moving mirror MV is shifted onto the optical axis of the device. The selected star must be placed into the central hole (it is seen as red circle when FOV illumination is on) of a glass plate CC, which is co-aligned with the field aperture to better than 0.2 mm (about $20''$). In this case, after removing of the mirror, light passes to DIMM and MASS detectors. Further star centering will be done by the DIMM software.

The viewer is not used in a normal work since the DIMM sub-device provides the telescope pointing at the star, star searching if necessary and guiding during measurements. In practice, the viewer serves as an auxiliary tool in extraordinary cases. The optical layout of the viewer is presented in Fig. 1.2, where the main viewer parts are shown.

Removable mirror MV has dimensions 12×18 mm. When inserted in the beam, it is placed at 40° angle with respect to the optical axis of the device. This provides the viewer axis tilt equal to 80° with respect to the instrument optical axis.

The re-imaging system of the viewer consists of two achromatic lenses V1 and V2 ACH18x50 (Edmund optics; focal length 50 mm, diameter 18 mm) and reproduces the instrument focal plane with magnification -1. The lenses are separated by 75 mm distance.

Standard $1\frac{1}{4}$ inches eye-piece with focal length $12 - 15$ mm is used with the viewer. The eye-piece is located at 220 mm from the axis of the device (or telescope) and about 40 mm from the back plane of telescope to provide easy access for the observer.

The viewer is placed in plane ZY (where a CCD camera is placed, too) and must be in a meridional plane of a fork mount when MASS/DIMM device is attached to telescope correctly. In this case the viewer doesn't limit telescope pointing.

Chapter 2

Mechanical design

2.1 General description

2.1.1 General characteristics

As it was shown above, there are two variants of combined MASS/DIMM device: for CTIO optical turbulence studies (CTIO variant) and for TMT site testing program (TMT variant). The CTIO program plans to use Meade telescope with 254 mm entrance aperture and the ST5 CCD camera as DIMM sub-device detector. For the TMT program, custom Cassegrain telescopes with 350 mm mirror are built. In this case, the ST7 CCD camera is used as the detector.

Different feeding telescopes and DIMM detector require some adaptation in the basic instrument design. For this, a few parts of the instrument were designed in two versions. These parts are:

- Instrument flange to install the device at telescope;
- CCD camera interface;
- Fabry lens holder;
- Exit pupil mask.

Due to the first two items, the devices differ a little in their overall dimensions. In the Fig. 2.2 and Fig. 2.3 these overall dimensions are shown. But the main box of the device is exactly the same.

The general view of combined MASS/DIMM device in CTIO variant is shown in Fig. 2.1. Practically all parts of the device are fabricated from hard aluminum alloy, black-anodized. Only few critical parts are made from steel. Total weight of the MASS/DIMM instrument is about 1.5 Kg.

The CTIO device is mounted at Meade telescope with the help of a casting nut having standard British thread. The TMT device is mounted with the help of 8 M6 screws.

The device electronics is enclosed in a separate case which can be removed and attached again easily. The connection to interior electronic elements, such as illumination LED and so on, is provided via a special plug connector.

The mechanical parts are designated on the drawings as "MDnnS", where MD – prefix for MASS/DIMM device, 'nn' – assembly unit number, 'S' — suffix for the specific part. The prefix is omitted when a designation is mentioned below.

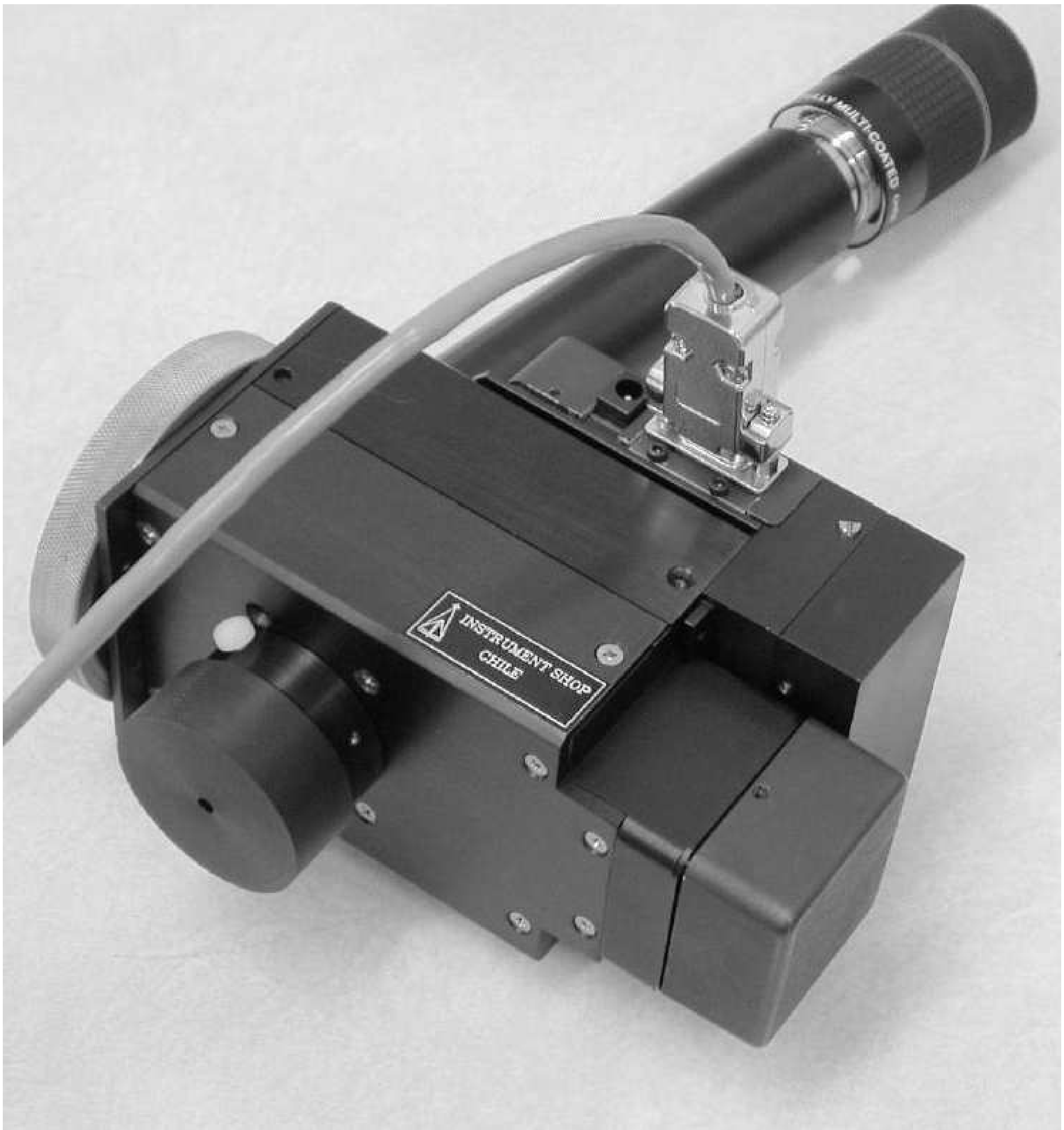

Figure 2.1: MASS/DIMM device for CTIO programs. View from the side of main beam **01C** and bottom tie **01D**. Instead ST5 CCD camera, the alignment tool is installed.

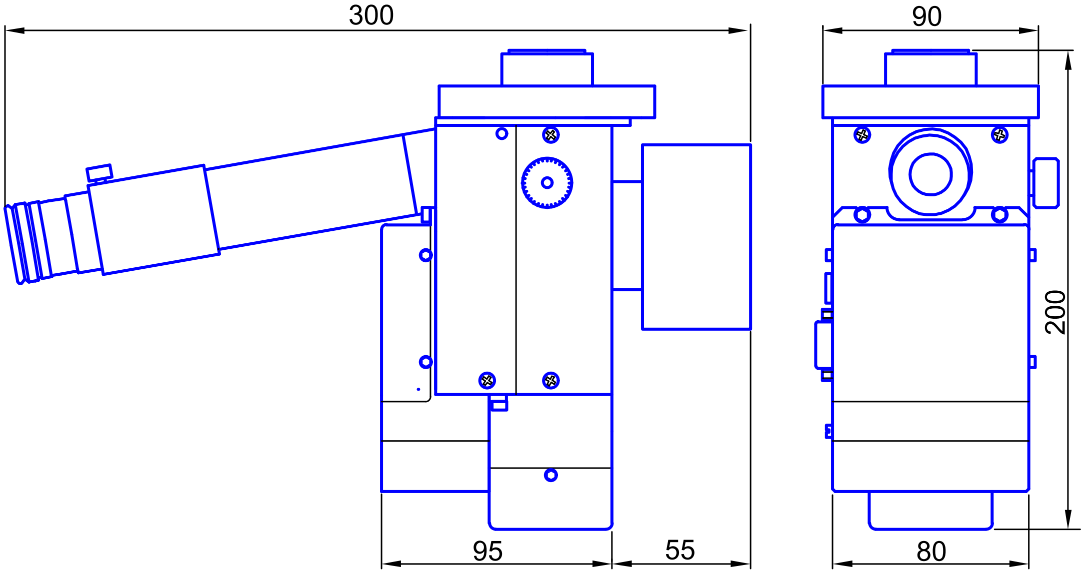

Figure 2.2: Main dimensions of the device with ST5 CCD camera for CTIO programs.

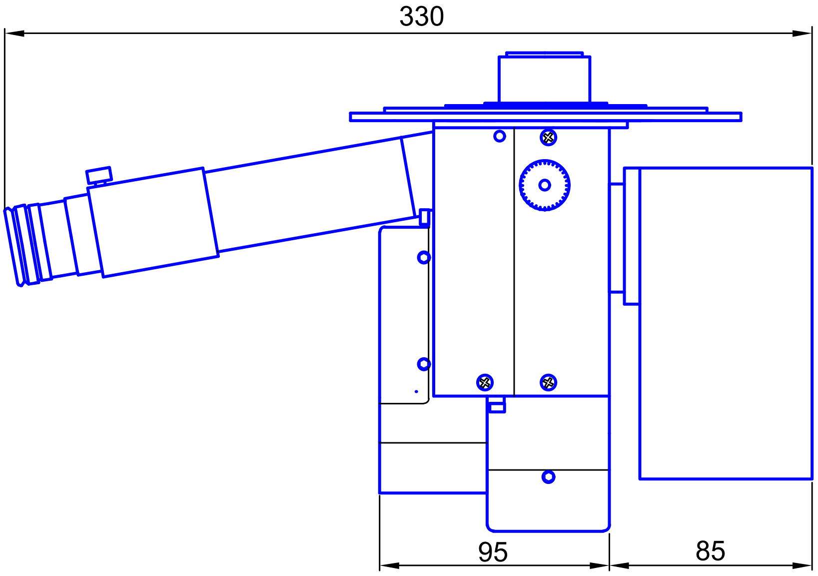

Figure 2.3: Main dimensions of the device with ST7 CCD camera for TMT programs.

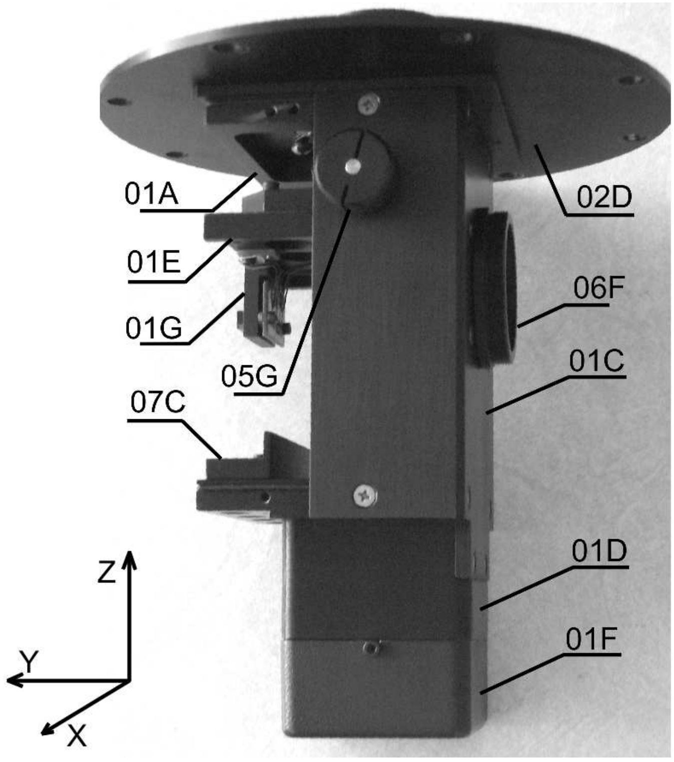

Figure 2.4: View of the device without cover. Used coordinate system is shown, too.

2.1.2 Device skeleton

The force structure of the device consists of 3 elements: device base **01A**, U-profile main beam **01C** and bottom tie **01D**. These parts are screwed together and form rigid through-like frame. One can see it in the Fig. 2.4, where photo of the device without cover **01B** is presented. This structure bears all other units and assemblies. Do not disassemble the device skeleton if there are other solutions!

Inside the device base, the mechanism for lateral shift of Fabry lens unit is mounted. On the outside, a mount ring (flange) **02D** is screwed. The latter holds the Fabry lens unit.

The transversal beam **01E** (called below – optical bench) is attached to the main beam. The optical bench bears most parts of the device optics. On the outside of the main beam, a CCD camera interface **06F** (or **06G** for TMT) is fastened. Also, the switching knob of the viewer mirror, 05G, is placed at one side of the beam.

The optical plate **04A** with PSU and DIMM re-imaging mirrors is mounted on the bottom tie and covered by **01F**. Also, the electronic box is set on the tie and fixed to the tie. Inside the device, the filter holder **07C** is screwed to the upper plane of the tie.

The cover **01B** (the second half of the device box) is fastened to the base and to the tie.

2.1.3 Optical bench

The optical bench **01E** is a central assembly unit of the device. On the top plane of the bench three functional units are mounted:

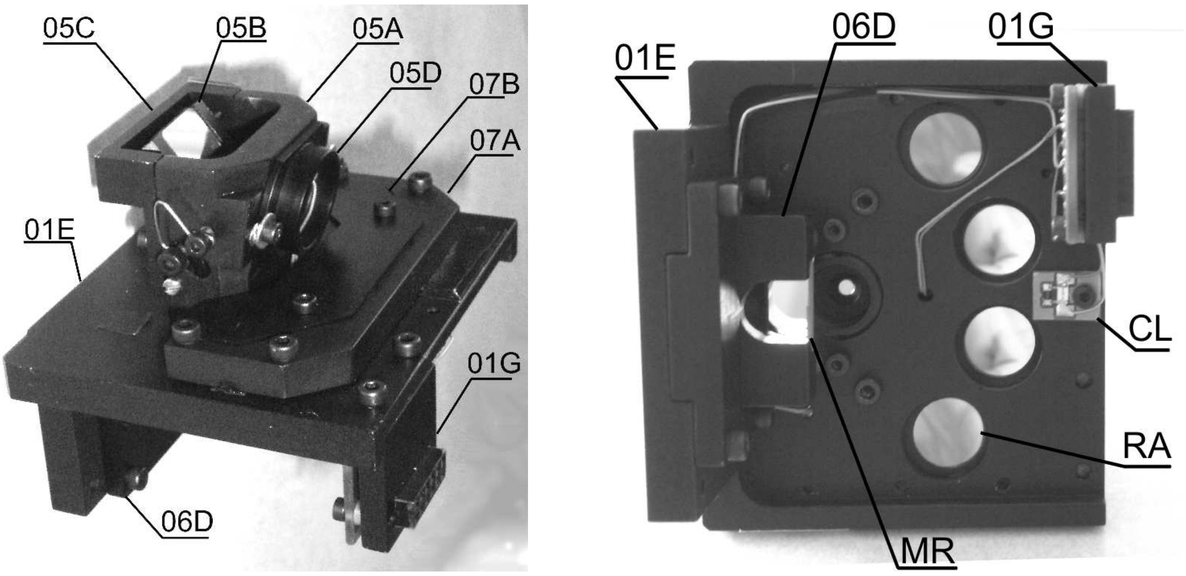

Figure 2.5: The top (left) and bottom (right) views of the optical bench.

- unit of the re-imaging mirrors RA, RB, RC, and RD;
- viewer removable mirror unit;
- focal plane unit.

On the bottom planes the folding DIMM mirror MR and the central blind are fastened. The top and bottom views of the optical bench are shown in the Fig. 2.5. On this photo the central blind is removed.

The re-imaging unit consists of the mirror support **07A** with sockets for mirrors, where the mirrors lie free, and the cover plate **07B**, which fixes the mirrors. The support is fastened to the optical bench with help of four M2.5 screws. The elastic separator between the part and the bench permits to adjust a little the total tilt of the mirrors holder.

The viewer removable mirror is a more complex unit. It contains the support **05A**, the clamping cramp **05C** which limits the mirror rotation and bears the Hall sensor plate, the mirror holder **05B** with two half-axes **05E** and **05U**, and the switching Ω-like spring. The mirror MV is cemented to its holder. Also, the cover plate **05D** which holds the glass plate CC with central hole is screwed to the support. Illuminating FOV LEDs are mounted at the cover plate. The plate CC is glued to the holder.

The focal plane unit includes the field aperture **06A** pressed into the socket of aperture support **06B**.

The folder mirror MR of the DIMM sub-device is supported by the special support **06D** to which it is pressed by the spring cover plate **06E**. The support itself can be aligned with help of 6 screws which fasten it to the optical bench. A blind **06C** is utilized to prevent direct light passing from the field aperture to the PMT photocathodes. It also reduces the scattered light from the exit pupil elements: DIMM mask, mirrors, holders.

All electronic parts placed in the main case of the device are located on the optical bench. The bench bears a connector for this electronics that matches the connector in the electronic box. More information about electronic elements which are inside the main box can be found

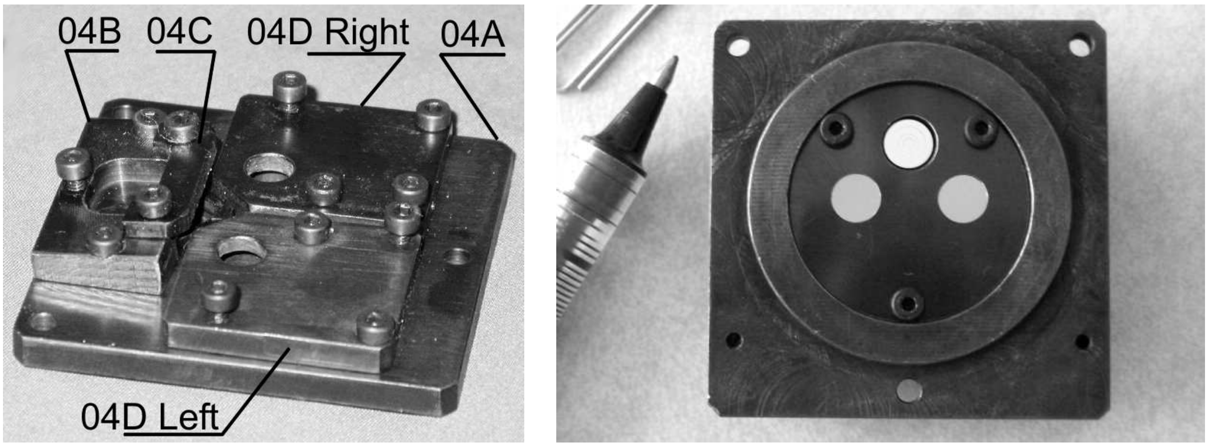

Figure 2.6: Left: view of the optical plate with PSU holder and two DIMM mirrors alignment plane. Right: view of the optical plate from inside the instrument.

in the Document [6]. In addition to the above-mentioned electronics, a Control light LED PCB is mounted to the bench directly.

2.1.4 Other assembly units

Fabry lens unit

The Fabry lens unit includes the shifted square nut **02B** with a thread for the Fabry lens holder **02A**. The thread serves to focus the lens. The lens itself is installed in the holder using a thin locking nut **02C**. The square nut is clamped between the device base and the mount ring. The clamp pressure is regulated by a wide brass washer which can be either corrugated or planished.

The lateral shift of the square nut with LF in one direction is provided by a cam **02F** with finger **02G** which transmits the motion of an adjusting screw to nut motion. For another direction, the second cam is installed. This mechanism is mounted under the device base, the fingers pass through the slots outside.

Viewer

The viewer consists of three parts: the eye-piece socket **03A**, the viewer tube **03b**. and the viewer flange **03C**. The latter is permanently screwed to the box cover. The re-imaging lenses V1 and V2 are installed in the sockets of the eye-piece part and of the viewer flange with the help of locking nuts **03D**.

Optical plate

The optical plate **04A** and other parts related to this unit are fabricated from steel to provide stability of the alignments for PSU and DIMM re-imaging mirrors. The external views of the plate are shown in Fig. 2.6. In the center of the plate a low central pad (height ≈ 0.6 mm) is placed. All three adjustable parts are pressed against this pad on one end.

The PSU holder **04B** is fastened by 3 screws — 2 pulled and 1 pushed. The DIMM mirror plates (right and left) **04D** are mounted by 3 screws too, but 1 pulled and 2 pushed. The fourth

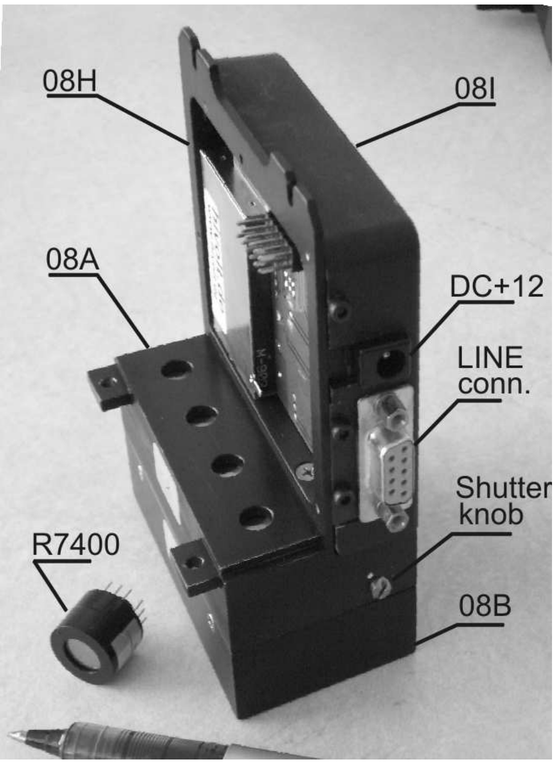

Figure 2.7: View of the detached electronics module. A photomultiplier PMT R7400 is shown separately. A pen on the photo is placed for comparison.

screw prevents the rotation of the mirror plate only.

The pupil segmentation unit is set in its holder with the help of the cover plate **04C**. The DIMM mirrors are cemented in the sockets of the mirror plates.

From opposite side of optical plate, a MASS/DIMM mask that defines the exact geometry of the exit pupil is fastened (see Sect. 1.2.3). The mask is produced from thin steel sheet.

The optical plate is mounted in the socket of the bottom tie of the device box. It may be removed and fixed back for checking or cleaning. The special cover protects the optical plate and its fixing and alignment screws.

2.1.5 Electronics module design

The electronics module (see Fig. 2.7) consists of two parts: the PMTs housing and the electronics case. The parts are screwed together and are not detachable from each other.

The PMTs housing **08A** contains 4 PMTs, 3 PCBs of the photon counting electronics, the teflon spacer **08C**, which prevents PMT photocathodes from contact with housing, and the shutter mechanism.

The shutter mechanism consists of two blades **08D** with holes, the cramp **08E**, the lever **08F**, and the axis **08G**. The axis passes through the hole in the housing, its rotation closes (clockwise) or opens (counterclockwise) the shutter. The shatter does not provide full darkness when the electronics is detached from the device, but protects the PMTs from direct daylight. The housing must be *always* closed with the cover **08B** when powered.

The PCB which bears auxiliary electronics, two external connectors, and the connector to the main-case electronics, is mounted on the frame **08H** of the electronics case. The cover **08I** protects the electronics from the outside. In the cover, a window for the LED indicators is made. When electronics is powered, the green LED shines. A presence of HV is indicated by the red LED and data exchange – by the yellow LED.

2.2 Alignment possibilities

Some alignment features are provided. Most of them are intended for assembly process only. Other alignments are done when the device is attached to the feeding telescope.

The alignments are:

- focusing of the Fabry lens;
- lateral shifts of the Fabry lens;
- tilt of the viewer mirror;
- centering of the CC plate;
- rotation a PSU segments around their axis;
- tilts of the PSU in XZ and YZ planes;
- tilts of the MASS re-imaging mirror assembly in two directions;
- tilts of the DIMM mirrors DM1 and DM2 in XZ and YZ planes;
- tilt of the folding DIMM mirror MR in YZ plane;

2.2.1 Common optics

The focusing of the Fabry lens is done by rotating the LF holder in the thread of the square nut **02B**. The error of 0.5 mm in the Fabry lens position produces the magnification error less than 0.5% and the shift of the entrance pupil plane along optical axis about ±100 mm. So, an accuracy of the Fabry lens focusing about 0.5 mm is more than sufficient. The full range of focusing of ±4 mm around the nominal position is provided. The nominal Fabry lens position depends on the particular feeding telescope.

The lateral shifts of the LF with an accuracy of about 0.1 mm (which corresponds to 1.5 mm in the entrance pupil) and with the full range of ±2 mm (±30 mm in the entrance pupil) in both directions provide practically identical shifts of the exit pupil in the PSU plane. This alignment is aimed to compensate for the imperfections in the Fabry lens centering and in the device centering and tilt. It is produced by two screws accessible via 3 mm holes in box cover **01B** with help of Hex1.5 key.

The inclination of the viewer mirror is fixed during the device assembly and should provide beam axis parallel to the viewer mechanical axis. The tilts are regulated with help of set screw in the viewer support cramp **05C**.

The residual offset of the on-axis star image from the viewer center may be eliminated by shifting manually the glass plate CC, up to ±1 mm in both directions.

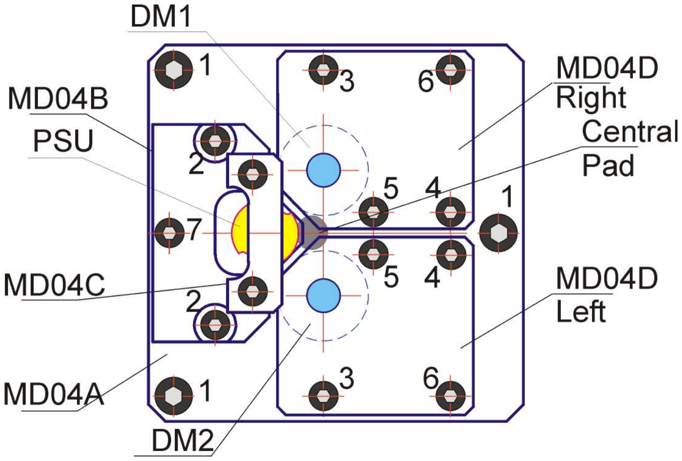

Figure 2.8: The optical plate with PSU in its holder and two DIMM mirrors alignment planes. 1 — screws M2.5 fixed plate to device, 2 — pull alignment screws M2 of the PSU support, 3, 4 — push screws M2 for alignment of the DIMM mirrors tilt, 5 — pull screws M2, 6 — anti-rotation screws, 7 - push alignment screws M2 of the PSU support. Screws 3 regulate distance between images, 4 align their vertical positions.

2.2.2 MASS sub-device optics

After the MASS segmentator is fixed in its place, the position angles of its segments should be tuned to their correct values of ±15 and ±45° ; the segmentator is inclined as a whole as well. The aim of these alignments is to direct the reflected beams precisely into the centers of the respective MASS re-imaging mirrors. The position angles must be set to within ±1° and the segmentator inclination is tuned with a precision of ±0.1° in both directions to place the beam spots in the re-imaging mirrors with sufficient accuracy. These alignments are provided by the push-and-fix screw pairs having the full range of about ±1.5° (this is enough, given the roughly correct initial segmentator setting under these angles).

Finally, to center the PSU images on the PMT photocathodes, the re-imaging mirror assembly is aligned with an accuracy not worse than ±0.2° (corresponds to the centering errors of about 1 mm on the PMTs). Given that the mirror supports are already made with correct angles, the alignment range of ±1° is sufficient.

2.2.3 DIMM sub-device optics

Similarly to the MASS channels optics, the initial setting of DM1 and DM2 mirrors is also made with the roughly correct angles. Precise alignment of them is aimed to compensate for the manufacturing and assembly imperfections and, more important, – to provide the two stellar images about 0.2 – 0.5 mm apart from each other in the CCD focal plane. This is the most fine tuning of the device optics since setting of the star images separation to within $\pm 5''$corresponds to the 5 μm shifts of the DM mirror supports. The DM mirrors are adjustable within the ±1° range which covers ±3 mm range on the CCD (see Fig. 2.8).

The tilt of the folding mirror MR should make the image plane parallel to the CCD surface. This tilt is not that critical, because the star is put always in the same place in the field of view during measurement. More important, that the star images must be located near CCD detector center. Note, that the tilt of re-imaging DIMM mirrors in YZ plane, producing the similar alignment, is strongly limited: when the tilt is small, the vignetting at folding mirror edge appears, otherwise – optical abberations are significant.

2.3 Disassembling and assembling

2.3.1 Disassembly sequence for alignment, maintenance or repair

Do not forget to close the PMTs shutter before disassembly of the device! Disassemble the parts only to the state needed for the device maintenance or optics alignment or cleaning. Some parts of the device can be removed without device opening, in arbitrary order:

- The Fabry lens can be removed with its holder only. Before, mark the position of the holder inside the square nut to re-establish the focusing at assembly.
- The viewer can be detached if the instrument is aligned and further work is planned in automatic mode. For this, unscrew the viewer tube with eye-piece together from viewer flange. Protect the first viewer lens V1 by a plastic cup (provided in the accessories).
- To check or clean a V2 lens, unscrew the viewer tube from an eye-piece socket.
- The electronics module can be detached to do some checks or alignments. Turn off the device, be sure that PMTs shutter is closed. Remove 4 M3 screws (2 near the viewer and 2 from the bottom tie) completely, then pull the electronics module away from device box, to unplug it from the internal connector.
- Optical plate with MASS PSU and DIMM re-imaging mirrors DMs can be removed to check the optics or the position of the exit pupil. First, slacken 2 screws M2.5 and remove the optical plate cover. When unscrewing 3 M2.5 screws (see Fig. 2.8) completely, support the plate by hand.

To provide access to the optics inside of the main device box, the cover **01B** must be removed. To do this: detach the electronics module first, unscrew 4 M3 screws — 2 which fasten the cover to the device base (near the viewer) and 2 which fasten the cover to the bottom tie. With some effort remove cover away in the Y-direction.

Then, the optical bench where most of the optics is installed, can be removed from the main beam. To do this, from external side of the main beam, unscrew completely 4 screws which are around the CCD camera interface. Flip the mirror in the viewer-on position to detach the mirror semi-axis from the groove in the mirror knob. Pull gently the optical bench out in the Y-direction.

Further disassembly is not recommended. If it is really needed, consult the designers for additional recommendations.

2.3.2 Disassembly of the electronics module

Disassembling the electronics module includes several steps, which must be done sequentially. To remove the PCB of power and auxiliary electronics, one must:

- unscrew 3 M2.5 screws which fasten the electronics cover **08I** and remove this cover;

- unscrew completely 2 M2.5 screws from the plate **08J** of DB9 line connector;
- unscrew 3 M2 screws that fasten the PCB itself;
- if it is necessary to remove the PCB completely, unsolder the HV yellow cable and disconnect the blue cable.

To change the PMTs or repair the counting electronics, do the following:

- unscrew 4 M2 screws from the PMT housing cover **08B** and remove this cover;
- unscrew completely 2 M2 screws from the counters PCB (connector side) and unscrew from the base the long M2 screw with teflon tube;
- disconnect this PCB and turn it by 180° ;
- unscrew 3 M2 and 2 M1.6 screws from the amplifiers PCB;
- with the help of a thin screwdriver (< 1.5 mm), begin to unscrew 2 M1.6 screws through the holes that are nearly opposite to the connectors edge of the PCB, simultaneously pulling up the PCB itself;
- when these screws are detached from the PMT housing, fold the PCB very carefully, pulling the PMTs out of the housing.

2.3.3 Assembly

Assembly is done in reversed order. A few recommendations may be useful for this process.

- When mounting the optical bench back to the main beam, pay attention to the position of the groove in the axis of the viewer knob. The mirror half-axis must hook into this groove. Be sure that the bench lies correctly in the beam before tightening finally the 4 screws.
- When installing the cover box back to the device, do not damage the rubber cord which is glued in the grooves of the bottom tie and the device base. Also, check that the connector on the optical bench is correctly inserted in the corresponding hole of the cover. Be sure not to leave a slot between the upper edge of the cover and the device base.
- When fastening the PCB, be sure that the PCB is laid correctly and tightly.
- When attaching the electronics module, be careful to insert the connector pins correctly into the matching connector on the optical bench.
- When installing the holder with Fabry lens, do not reverse it. The more convex surface of the Fabry lens must face the telescope.

Chapter 3

Alignments

3.1 Preliminary alignments

Preliminary MASS/DIMM optics alignments are performed during device assembly. These alignments include a correct placement and tilt of the optical elements to provide light pass through MASS and DIMM channels. Alignment possibilities were described above in Sec. 2.2. To align the optics, one will need to prepare some additional tools: a kind of the optical test bench, the laser light source, and a telescope model (see below).

The optics test bench may be arbitrary but providing enough rigidity and the source-to-MASS distance of the order of 0.5 – 1 meter. The attachment of the device to the bench must provide the possibility to adjust the position of the light source (laser beam) with respect to the device in two directions.

The semiconductor laser of no more than 3 mW power is set on the opposite end of the bench. The variable resistor of a few KOhm is recommended to be connected sequentially with the laser to adjust laser beam intensity. The laser support must also allow the slight corrections by angle.

In addition, one needs the weak negative lens to attach to the laser to make the slightly divergent beam. It is needed to illuminate homogeneously the entrance pupil of the model telescope. The latter is attached to the device instead of the Fabry lens holder and consists of the good-quality objective lens (focal length about 50 mm) and the pupil diaphragm of the size about 5 mm set in front of the objective at the distance equal to the lens focal distance. The telescope focusing should be possible.

3.1.1 MASS PSU alignment

Before installing the PSU, rotate its segments around rotation axis according to Sec. 1.3.1. Namely, if seen from the PSU base side, the rotation angle is defined by groove in the base of each segment. Note that the D–segment base is closest to the PSU handler and the A–segment base is uppermost. The segments must be rotated with respect to the YZ–plane by following angles: D — at 45° and C — at 15° counterclockwise; B — at 15° and A — at 45° clockwise. Do not tighten the PSU cover plate.

Switch on the laser and direct its beam into the field aperture. Incline the device by about 3° in YZ plane or shift the laser to provide that laser beam falls on the PSU installed. If the laser beam is wide enough (but no lens is installed in front of the laser), all four segments of the

PSU will be illuminated. Otherwise, firstly point the beam on the largest D–segment. One can see the reflected beam spots near the re-imaging mirrors.

Correct the segments orientation will direct the beams onto the mirror centers. With help of a thin screwdriver or awl, rotate the first D–segment in such a position that the reflected beam falls closest to the center of D–mirror. After this, try to align the segment C similarly, fixing the D–segment orientation with help of another screwdriver. Then proceed with B and A in the same fashion. It is evident that, having the widest beam, the D–segment is most critical in alignment. After finishing the tuning of rotation angles of segments, tighten the PSU cover plate.

In principle, it is possible to use a special mask with the marked mirror centers put atop of the mirrors, but normally the laser beam spots are sharply seen at mirror surfaces.

After doing these rotating alignments, try to set the beams closer to the mirror centers using tilts of the PSU support with help of 3 screws (No 2 and 7 on Fig. 2.8). Normally, a combination of the proper tilt of the PSU support and appropriate rotation angles of the segments provide the reflected beams falling close enough to the re-imaging mirror centers that no light is lost somewhere in the further path due to vignetting.

There is no individual alignment for each re-imaging mirror. The support of those mirrors as a whole can be tilted slightly in two directions. This permits to align a little the position of segment images built by re-imaging mirrors RA, RB, RC, and RD on the PMT photocathodes. To check the correct position of the images, a special mask can be used. The exact positions of the PMT photocathodes with respect to electronics module reference plane are shown in Fig. 3.1. The manufacturing accuracy is sufficient to provide right image centering on the PMT photocathodes.

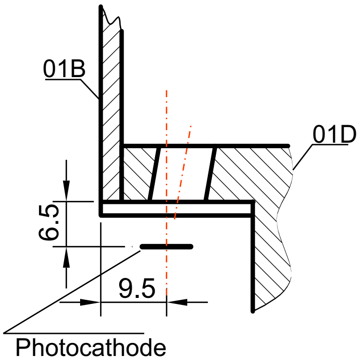

Figure 3.1: Photocathodes position with respect to the reference plate of the bottom tie.

Pay a special attention to D–segment image, because it is the largest one. To check the pupil images as they will be on photocathodes, attach the model telescope to the device. With help of a negative lens, produce the divergent laser beam, focus the model telescope. In the dark room, the images of segments are seen on the paper mask placed in the plane of PMTs photocathodes. Also, the images can be observed directly using a magnifying lens when PSU is illuminated by any scattered light.

3.1.2 DIMM sub-device preliminary alignment

Before DIMM sub-device alignment, remove the main blind **06C**. First approach can be done without model telescope. If the field aperture is illuminated by scattered daylight, it is possible to see its image in the plane of a CCD detector. With help of alignment screws No 3 and 4 at the optical plate (see Fig. 2.8), put the images built by right DM1 and left DM2 re-imaging mirrors into the center of CCD detector. To locate the center, a special tool can be used (Fig. 2.1).

The aperture images must be illuminated uniformly. If some vignetting is observed, this means that folding mirror has an incorrect tilt. The alignment of its support may be done. As a rule, accuracy of the support fabrication is sufficient to skip this alignment.

Install the model telescope on the optical axis of the device. Produce a "star" image in the focal plane of the instrument. In the focal plane of CCD detector, two "star" images will be observed. **This procedure must be done with the faded laser intensity!** Align the position of images vertically and horizontally. The images must be point-like without any noticeable abberations.

The described alignments are normally done in the laboratory once after the device optics assembly. The rest alignments related to the installation of the device on the feeding optics are described below.

3.2 Device alignments at the telescope

3.2.1 Fabry lens position

First alignments after the device attachment to telescope are convenient to do with the transparent plastic mask, where the size and position of the exit pupil are drawn on the front side. The mask is mounted definitively instead of the optical plate **04A**. The mask permits to do lateral alignments of the Fabry lens and focusing the lens. Also, electronics module must be detached.

Illuminate well the entrance aperture of the telescope or point telescope at the bright object such as a white wall. The image of the entrance aperture of the telescope pupil can be viewed directly on the mask or with help of a magnifying lens. Put this image in the center of the marked circle, rotating the alignment screws of LF lateral shift.

Place some flat opaque object (mask) with a sharp edge (e.g. a paper stripe) into the plane of the entrance pupil (top end of the telescope tube). Observe the image of this mask in the plane of exit pupil. If the Fabry lens is focused well, the pupil image with a mask shadow will be seen sharply. Otherwise, remove the side cover **01B** and optical bench **01E**. After this, it is possible to rotate Fabry lens holder in needed direction.

The LF shift can be estimated with help of the Fig. 3.2. For this, move the mask away from the telescope top at about 0.5 m. If the mask image sharpness will improve, then LF is located too far from the focal plane of the instrument. Rotate LF holder counterclockwise at 2 revolutions. Repeat the procedure again to reach the correct LF focusing.

Then check the correct position of the exit pupil again. When Fabry lens is focused and laterally aligned, remove the plastic mask, install the optical plate and the optical bench.

To check MASS channels, look at PSU through PMT holes with help of a lens. Segment images must be uniformly illuminated without any vignetting.

Install CCD detector on the device. Illuminate the entrance of the telescope as for LF alignment case. Take the series of images with the CCD camera. The images of the field aperture will be seen in frames. When ST5 camera is used, the diameter of the field aperture image is a little larger than the frame size. With help of screws 3 and 4 (Fig. 2.8) place symmetrically

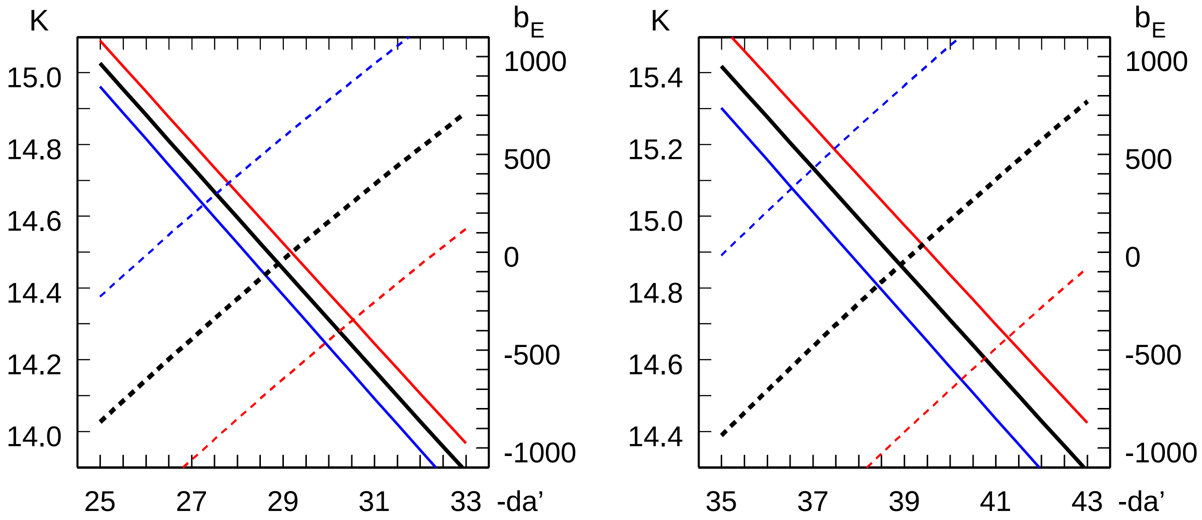

Figure 3.2: System magnification K and entrance pupil plane position b_E dependence on the Fabry lens focusing. Left: MASS/DIMM for CTIO programs, on right — for TMT programs. $-da'$ is a distance between the device focal plane and LF. Black line — for nominal focal length (125 mm and 140 mm), blue — at 1.5% less, red — at 1.5% greater.

the right and left images (overlapped) on the frame. Distance between right and left overlapped images has to be about 50 pixels.

Note, that sharpness of the aperture image edges may be not ideal. Nevertheless the telescope focusing permits to have well focused star images.

Point telescope to some star. Doubled star image must appear in the CCD frame. Focus the telescope and correct telescope pointing to provide the images in the center of the CCD frame.

The CCD frame orientation depends on how the CCD is installed at its interface. Put the CCD frame columns along the Z-axis of the device. In this orientation, the images must be separated horizontally (see Fig. 4.1).

Make alignments of images separation, not letting them to shift vertically. Close the cover of the optical plate.

3.2.2 Viewer alignment

When a star image is located in the center of aperture (it can be checked again by a partial illumination of the telescope entrance) the viewer can be aligned, too. Look in the viewer. To see an illuminated central hole, attach the electronics module.

If the star image is offset from the center of the illuminated circle, one needs to detach the side cover and loosen the CC glass holder fixing screws. Using a magnifying lens for controlling the star image in the glass hole, move the holder until star drops in the center of the hole. Very precise alignment is not needed here. When done, tighten the screws to fix the glass holder to the viewer mirror support and mount the side cover **01B** at the device (see Sect. 2.3.3). Looking in the viewer, check focus. Viewer focusing is made by eye-piece shifting in ocular tube.

Chapter 4

Critical parameters determination

4.1 System magnification

As it follows from Sect. 1.2.1, a system magnification depends on parameters of the telescope optics as well as parameters of the MASS/DIMM optics. The system magnification transforms the physical dimensions of the pupil segmentation elements into the sizes of the instrument annular entrance apertures which are included in the theoretical formulae. Therefore, exact system magnification is needed for MASS sub-device correct work as well as DIMM work.

The measurement of the system magnification has to be performed in a dark room. All the alignments and a real telescope focusing must be done before.

Remove the electronics module. Put some strong light source in front of the channel D hole in the bottom tie **01D** (the hole closest to the connectors side) to get the segmentator fully illuminated. The size of the source must be not less than 4 mm, which is the D-segment image size on the photocathode created by the re-imaging mirror. The location of this source has to coincide with the D-segment image place; light beam from the source must be directed in the Channel D re-imaging mirror. If the source is not large enough, displace it from the position of the D-channel photocathode. Note, that angle between device axis and direction to the re-imaging mirror is about 15° in the YZ plane.

The segment D image is built in the entrance pupil plane of the MASS/DIMM + telescope system. It has a blue-green color due to the selective reflection by re-imaging mirror. The edges of the segment D image are easily examined with a magnifying lens. Put a transparent ruler or other precise measurement tool in the plane of the entrance pupil. Use a magnifying lens to see simultaneously the D-segment image edges and the ruler clearly. Measure the outer and inner diameter of the image.

Alternatively, some semi-transparent screen (paper) may be placed in the plane of the entrance pupil and, if the light source is bright enough and well collimated (like LED flash), one can see directly the D-segment image. Mark the edges of the image on the screen. Then, measure the picture by any ruler.

While examining the edges of the D–segment image, make sure that there is no vignetting in the system (edges are equally sharp, vertical size is equal to the horizontal size).

Similarly, repeat the same procedure putting the light source in channel C. This helps to control the magnification obtained by measuring D–segment. Note, nevertheless, that the less image size which is measured, the less precision of the magnification is obtained.

The magnification of the system is obtained by division of the measured sizes by the corresponding physical diameters of the segment D and C of the segmentator (see Table 1.4). If the image is well-focused, the precision of image size measurement of the order of 0.5 mm is easily achievable and is more than enough for our purpose. Check the matching of these estimations, compute the mean magnification value and put it in the `device.cfg` file.

4.2 DIMM scale

DIMM scale in the CCD detector plane is critical to transform a measured *rms* in CCD pixels into arc-seconds. Real scale may differ from preliminary value (see Table 1.6). Determination of DIMM CCD scale must be done after the all device alignments are finished and feeding telescope is focused exactly.

The best way to obtain the scale is taking a CCD image of a known binary star with a separation between its component in range $20''$— $60''$. The magnitude difference between components is preferably less than 3^m.

In the Fig. 4.1, part of the CCD frame is presented. One can see two pairs of images. Separation between images of the same brightness is defined by DIMM re-imaging mirrors DMs alignment. Distance between bright and week components in the given example is known as $25''$. To determine the scale factor, this distance must be measured on the frame in pixels with help of any graphics program which provides pixel coordinates output. Depending on DIMM software requirements — a scale constant in arc-second/pixel or pixel/arc-second must be the calculated.

In the given example, the scale value of $0.99''$/pixel was found.

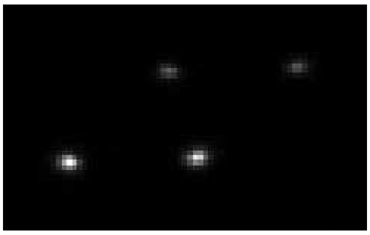

Figure 4.1: CCD image of the binary star HR8895 obtained for scale determination.

4.3 MASS detectors parameters

4.3.1 PMT optimal voltage and discrimination determination

In order to choose the working point (optimal HV level common for all PMTs, and individual discrimination levels), one needs to conduct the counting characteristics registration.

Counting characteristics are recorded using the `Detector Counting measurement` function of the Turbina program (Menu `Tools`) (see [11]). Since the fluxes from the control light differ much in different channels, at least two levels of the control light are recommended to set in the sequence, to have the curves with the plateau fluxes from 300 to 1000 pulse/ms. With lower signal level, the precision of the non-Poisson parameter is degraded, with bright light, the strong non-linearity is already encountered. An additional control light level equal to zero (0) must be set in a sequence to get the dark current characteristics.

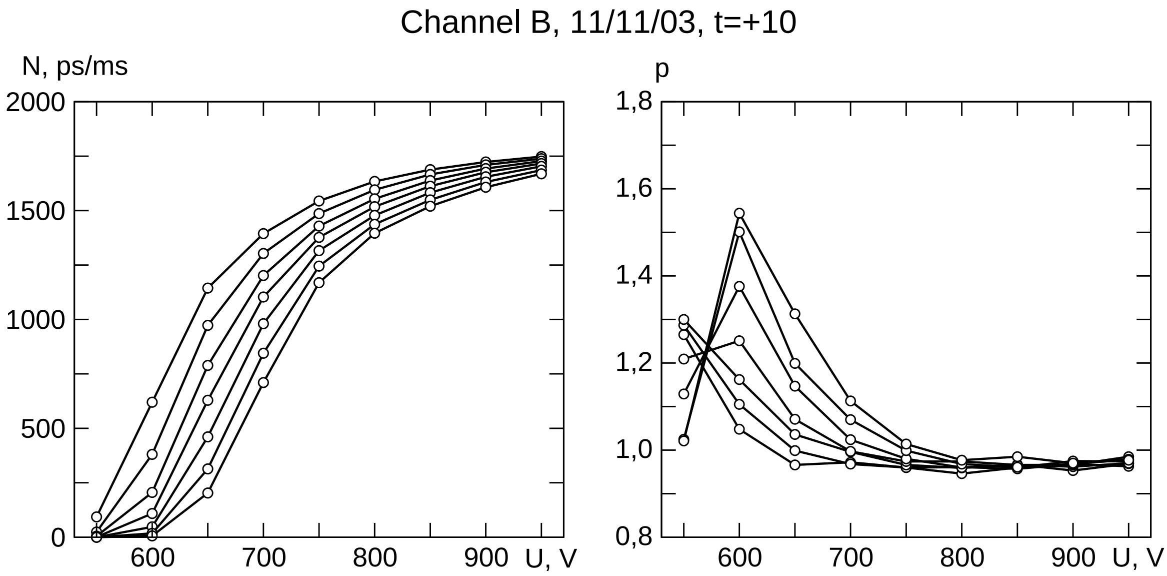

Figure 4.2: Light counting functions. Left: Flux dependence on the high voltage for 7 threshold levels (0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9 mV), lowest curve corresponds to the 0.9 mV level. Right: Non-Poisson parameter as a function of Voltage for 7 threshold levels, here lowest curve corresponds to the 0.3 mV threshold.

The grid of high voltage levels covers normally the range 550 to 950 V with a 50 V step. While fine-tuning the settings subsequently, the step and range may be lowered. The discrimination threshold level is tuned within a range from 0.3 to 0.9 mV with a step 0.1 mV. These input parameters for the measurement are set in `turbina.cfg` file in the Section `Operations` SubSection `Detectors counting measurement`.

The accumulation time of each point should be long enough for the reliable estimate of non-poissonity. The estimate of the precision of its determinations is:

$$\epsilon_p^2 = \frac{2}{N}(1 + \frac{1}{F}), \qquad (1)$$

where N is a total number of micro-exposures, F is a mean count per micro-exposure. In practice, to achieve the relative precision of p about 0.5% one needs the accumulation time more than 100 s at high fluxes. This implies about 2–4 hours process for the total cycle of measurements.

Since the drifts and temperature dependences are possible, the repetitive measurements for checking the working point stability are necessary. These measurements can be done with a narrower range of input parameters to economize time.

The dark current characteristics are aimed to determine the range of the HV level and discrimination thresholds where the dynode or pulse amplifier noise is negligible.

For making the light characteristics, one needs to measure the relations of both flux and non-Poisson parameter p on the HV level U. An example of such relations is given in Fig. 4.2.

From this figure it follows that the high voltage must be not lower than 800 V. The counting characteristics become flat enough, fluxes depend weakly on the discrimination threshold and the non-Poisson parameter approaches the value about unity only above this value. Note, nevertheless, that for the threshold of 0.9 mV the HV has to be not less than 900 V to provide a low slope of the HV dependence. On the other hand, the HV of 800 V is quite enough for the threshold of 0.5 mV.

It is better to use HV as low as possible. Since the HV value is common for all the PMTs, joint analysis must be done. Doing this, keep in mind that non-Poisson parameter is most critical for PMT in the channel A. Note, that the upper limit for PMT R7400 is 950 V and this value should not be selected for a long term usage.

An additional constraint is the over-light protection. Note here, that since the relation of an average anode current on the high voltage supply is quite steep, the safety limit of the over-light system (counted in pulses per second) decreases significantly when the HV level grows.

4.3.2 Non-linearity and Non-poissonity determination

In order to treat correctly the photon statistics and compute the correct scintillation indices, one has to know the non-linearity parameter τ and the non-Poisson parameter p. Correct value of the parameter τ is critical at high fluxes (in C and D-channels), while an exact value of the parameter p is needed at low fluxes (in A and B-channels).

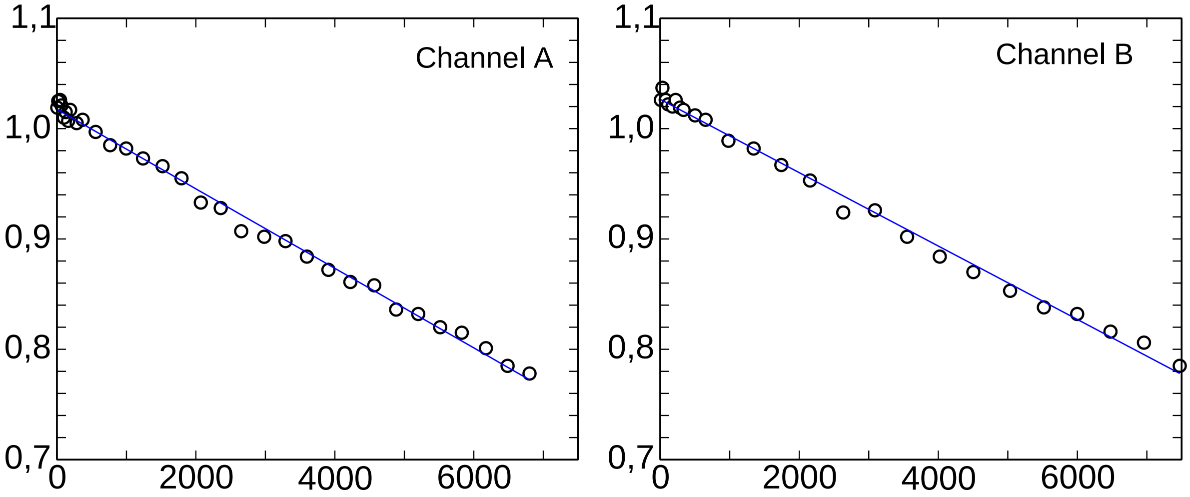

Figure 4.3: Dependence of non-Poisson parameter p on flux F for A and B channels. Line is linearly fitting the measured points.

Both these parameters are derived from the dependence of p on the light flux F which needs to be specially obtained. To get the p–F relation (see previous section), one can use the special function `Detector Statistics measurement` in the Turbina program, placed in menu item `Tools`.

The measurements of flux F and non-Poisson p values are made with currently set values of the discrimination thresholds of counters and high voltage level. The grid of the control light relative intensities is supplied dense enough to get the needed precision of the output parameters. Some fifty values from 0.0 to 1.0 with a step 0.02 are recommended. The duration of one point measurement is determined by the formula (1) and may be of the order of 40 sec or more. These input parameters for the measurement are set in `turbina.cfg` file in the Section `Operations` SubSection `Detectors statistics measurement`.

The typical relation of the non-poissonity p on the average flux in channels A and B is shown in Fig. 4.3. It is clear that this relation is practically linear. It should be noticed meanwhile that the better fit is obtained with a quadratic approximation of the relation.

Use the least-square method to get the linear regression coefficients (the handy graph-plotting program `xmgrace` provides such a possibility as many others). The crossing point of a line fit with the p-axis (constant term in regression) determines the parameter p. The line slope in the point of zero flux is equal to -3τ where the non-linearity τ is expressed in milliseconds if the flux F is counted in pulses per milliseconds. The slope of fitting line in the Fig. 4.3 corresponds to a non-linearity parameter about 12 ns.

Appendix A

Optical parts specifications

A.1 The specifications for MASS/DIMM purchased optical elements

Des.	Part and parameters	Manufacturer	Stock name/number	Total q-ty	Rem.
LF	**Fabry lens**				
	for TMT	Melles Griot	01LAO139	1	1
	Focal length: 140 mm				
	Diameter: $25.0^{+0.0}_{-0.2}$ mm				2
	or				
	for Meade	Edmund Optics	ACH25x125MgF2 TS	1	3
	Focal length: 125 mm		NT32-492		
	Diameter: $25.0^{+0.0}_{-0.2}$ mm				
V1,2	**Viewer lenses**	Edmund Optics	ACH18x50MgF2 TS	2	3
	Focal length: 50 mm		NT32-913		
	Diameter: 18 mm				
K	**Kellner eyepiece**	Any	—	1	
	Focal length: 12 mm				
	Barrel diameter: $1\frac{1}{4}$ inches				

1. See specification at www.mellesgriot.com
2. Ask to reduce a factory diameter 30 mm while ordering
3. See specification at www.edmundoptic.com

A.2 The specifications for MASS/DIMM special optical elements manufactured by the contractor

Des.	Part and parameters	Part number	Ref.	Total q-ty	Rem.
MV	**Removable mirror**	OP4	op4.dwg	1	1
	Size: 12 × 18 mm				
	Substrate: BK7 glass				
	Thickness: 2 mm				
	Surface Accuracy: $\lambda/4$				2
MR	**DIMM folding mirror**	OP3	op3.dwg	1	1
	Size: 10 × 15 mm				
	Substrate: BK7 glass				
	Thickness: 3 mm				
	Surface Accuracy: $\lambda/10$				2
RA-D	**MASS mirrors**	OP1	op1.dwg	4	1
	Diameter: 12.8 mm				
	Curvature radius: 102 mm				
	Substrate: BK7 glass				
	Thickness: 3 mm				
	Surface Accuracy: $\lambda/4$				2
DM1,2	**DIMM mirrors**	OP2	op2.dwg	2	1
	Diameter: 10.8 mm				
	Curvature radius: 136 mm				
	Substrate: BK7 glass				
	Thickness: 5 mm				
	Surface Accuracy: $\lambda/10$				2
PSU	**Segmentator**		md10a.dwg	1	1
	Diameters: see Tab. 1.4		md10b.dwg		
	Curvature radius: 250 mm		md10c.dwg		
	Substrate Material: Hard bronze		md10d.dwg		
	Surface Accuracy: $\lambda/4$				2
CC	**Circle reticle**	OP6	op6.dwg	1	3
	Central hole 1.6 mm				
	Thickness: 1.0 mm				
	Diameter: $13.0^{+0.0}_{-0.2}$ mm				
SF	**Spectral filter**	OP5	op5.dwg	4	
	Diameter: 11 mm				
	Surface Accuracy: $\lambda/2$				2

1. Coating: Protected aluminum, R avg. $> 87\%$
2. Surface Quality: 40 – 60 scratch and dig over central 95% of surface

Appendix B

List of mechanical parts

Des.	Part	Material	Q-ty	Rem.
AS01	**Box**			
MD01A	Device base	HA	1	C
MD01B	Box cover	HA	1	S
MD01C	Main beam	HA	1	C
MD01D	Bottom tie	HA	1	C
MD01E	Optics bench	HA	1	C
MD01F	PSU cover	CA	1	S (Update of 1590LBBK enclosure)
MD01G	Connector support	HA	1	S
AS02	**Fabry lens unit**			
MD02A	Fabry lens holder	HA	1	R (/C - for TMT, /M -for Meade)
MD02B	Shifted square nut	HA	1	R
MD02C	Locking nut No.1	HA	1	S
MD02D	Mount ring	HA	1	R (/C - for TMT, /M -for Meade)
MD02E	Casting nut	Steel	1	R (only /M -for Meade)
MD02F	Cam	HA	2	S
MD02G	Cam finger	Steel	2	S
MD02H	Cam axis	Steel	2	S
AS03	**Viewer**			
MD03A	Ocular socket	HA	1	R
MD03B	Viewer tube	HA	1	R
MD03C	Viewer flange	HA	1	R
MD03D	Locking nut No.2	HA	2	R
AS04	**Pupil segmentation unit**			
MD04A	PSU support	Steel	1	C
MD04B	MASS segmentator holder	Steel	1	C
MD04C	Cover plate	Steel	1	S
MD04D	DIMM mirror plates	Steel	2	C
MD04E	Aperture mask	Bronze	1	S (/C - for TMT, /M -for Meade)

List of mechanical parts. Continuation

Des.	Part	Material	Q-ty	Rem.
AS05	**Viewer mirror unit**			
MD05A	Support	HA	1	C
MD05B	Mirror holder	HA	1	C
MD05C	Clamping cramp	HA	1	S
MD05D	Cross cover plate	HA	1	R
MD05E	Right axis	Steel	1	R
MD05F	Knob axis	Steel	1	R
MD05G	Switching knob	HA	1	R
MD05H	Bushing	Steel	1	S
MD05U	Left axis	Steel	1	R
AS06	**Focal unit and CCD interface**			
MD06A	Field aperture	Steel	1	R
MD06B	Aperture support	HA	1	R
MD06C	Central blind	HA	1	R
MD06D	Folding mirror support	HA	1	C
MD06E	Spring cover plate	Steel	1	S
MD06F	CCD interface	HA	1	R (/C - for ST7, /M -for ST5)
MD06G	Interface base	HA	1	R (/M -for ST5 only)
AS07	**MASS optics holders**			
MD07A	Mirrors sockets	HA	1	C
MD07B	Mirrors cover plater	HA	1	S
MD07C	Filters sockets	HA	1	C
AS07	**Electronics box**			
MD08A	PMT house	HA	1	C
MD08B	PMT cover	HA	1	S
MD08C	Teflon spacer	TF	1	S
MD08D	Shutter blade	Steel	2	S
MD08E	Shutter cramp	Steel	1	S
MD08F	Shutter lever	Steel	1	S
MD08G	Shutter axis	Steel	1	S
MD08H	Electronics frame	HA	1	C
MD08I	Electronics cover	CA	1	S (Update of 1590SABK enclosure)

Table B contains the list of mechanical parts which are needed for production of the MASS/DIMM device. The parts are grouped in assembly units. Quantity is given for one copy. Remarks ”S”, ”R”, ”C” are the assigned ranking estimations of the part work-consuming — simple, rotation-symmetry and complex. Needed fasteners and standard items are not included in this table.