ELT 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, modified for ELT site testing program, according to the Proposal to European Southern Observatory (ESO) [1]. The project is implemented in frame of the ESO contract No. PO007467/GWIE.

The MASS/DIMM optical scheme was specially calculated for the use with Celestron 11 feeding telescope. Nevertheless, the two components Fabry lens unit permits to use the instrument with other similar telescopes.

The principles of the work of MASS and DIMM components of the combined instrument are described in [6], [4], and [11]. The combined MASS/DIMM instrument for CTIO and TMT site testing operations was designed three years ago [9]. Meanwhile, according to the experience obtained in a year-long exploitation of these devices, some changes have been introduced in the geometry of the main optical component of MASS – the 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 CCD camera ST2000MX which was planned for use with MASS/DIMM instrument.

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.

The electronics of the device and details related to it are presented in a separate document [8]. Also, separate documents contain Turbina Software reference guide, Turbina user guide [13], and Supervisor user guide [10], which complete the full description of the MASS/DIMM instrument and its control software.

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Chapter 1

Optics design

1.1 Basic principles

Here we briefly remind 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 on the turbulence intensity, on the aperture geometry and on the spectral range (this dependence is reflected by the so called weighting function $W(h)$ [6, 7, 12]).

Using these 10 measured index values, calculation of some integral characteristics of the atmospheric turbulence and restoration of the vertical turbulence profile with low-resolution (5 – 6 fixed layers) are possible. All the weighting functions drop to zero at zero altitude, so the ground layer is not sensed.

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 along the full light path in the atmosphere. So, the weighting function for DIMM does not depend on altitude.

The idea to combine two different turbulence measuring devices in one was brought from the following facts:

- Multiaperture scintillation sensor (MASS) does not sense a turbulence located below 1 km above ground (boundary, ground layers). Possible solution — a generalized mode of the MASS measurement, was tested with original MASS device. It was found that this method is capable of giving reasonable results with large aperture feeding telescope only. On the other hand, DIMM equally sensitive to both low and high turbulence.

- When a Cassegrain-type small telescope is used to feed a DIMM device, only two circular parts of the entrance pupil (about 15% of area) are used. MASS device uses even less part of the entrance pupil. Note that the original MASS with a set of entrance apertures having 13 cm largest aperture requires 40 cm or larger Cassegrain-type telescope.

- Numerical simulations show [7] that reducing the largest MASS annular entrance aperture (the segment D) down to 8.5cm improves the method sensitivity for middle altitudes. This means that a non-expensive (amateur class) telescope with a diameter 25 – 30 cm can be used to feed the MASS device.

The following general solution was chosen and implemented in the 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 help of a segmentator unit (see [4]) onto four MASS channels, and to re-image the exit pupil at 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 to obtain the needed separation.

The following Sections describe this process in detail.

1.2 Principal geometry of MASS–DIMM device

Principal geometry of ELT MASS/DIMM device does not differ from optical scheme used in CTIO MASS/DIMM device. As in CTIO device, the Fabry lens (LF) is placed before the focal plane F of the telescope. In this case the Fabry lens shifts the focal plane to the new position F' (focal plane of the instrument) where the field diaphragm is placed.

This plane is fixed relative to the feeding telescope at distance c from the pole (nominal location) of the primary mirror M1. Also, the plane F' is fixed with respect to the segmentator S at distance a. MASS/DIMM device contains complex pupil segmentator unit (PSU) including both the MASS channel segmentator and DIMM channel mirrors. These segmentators direct light towards the MASS channel and DIMM channel, respectively.

The position and focal length of LF must satisfy two conditions simultaneously:

- Precise focusing of the image of a target star in the field aperture critically needed for DIMM channel.
- Coincidence of the exit pupil plane with plane of the segmentators.

Our calculations (see [2]) show that in order to meet these two demands for the C11 telescope the two components Fabry lens must be used.

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 the optical axis of the instrument. In fact, the Fabry lens re-builds not the original entrance pupil but its image produced sequentially by the primary and secondary mirrors of a telescope. The dimension and location of this image depend on the exact geometry of a telescope, and slightly change when a telescope is refocused.

Note, that in case of a simple refractor with one objective lens, entrance and exit pupil practically coincide, so the magnification of the telescope itself is 1.

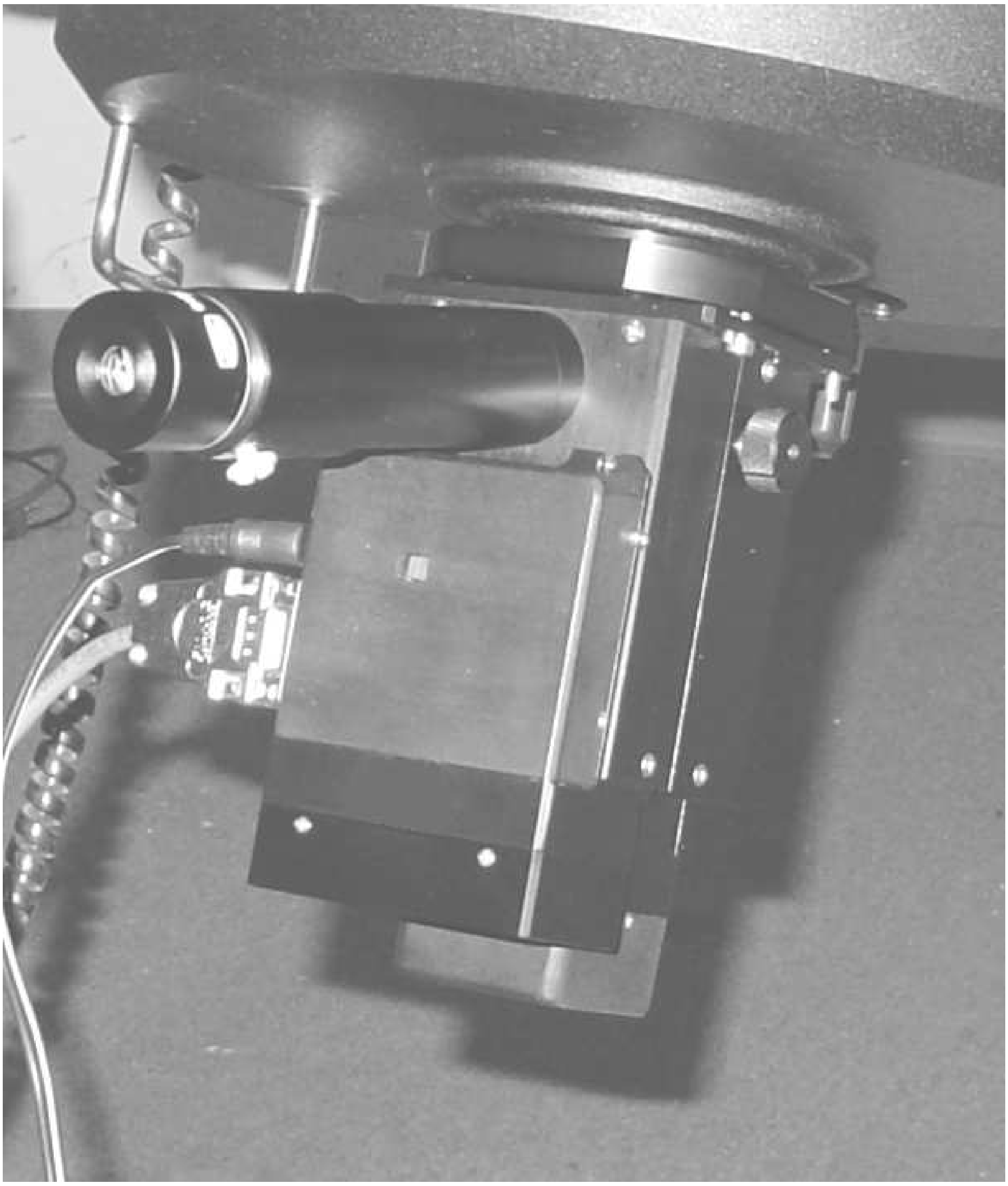

Figure 1.1: ELT MASS/DIMM device at the telescope C11. View from the side of the viewer and electronics box.

In case of two mirrors optical system, the telescope itself produces some magnification, because its entrance pupil is larger than exit one. With enough accuracy, the telescope magnification $K_T = F_1/F_2$. For the Celestron 11, this value lies between -3.668 and -3.214 due to uncertainty of the assumed telescope parameters.

The ratio of the diameter of an aperture in the entrance pupil plane to the diameter of the respective physical element placed in the exit plane, is the magnification K of the instrument. It depends on the 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 the telescope tube). Such a position is very convenient for instrument check and alignment.

The nominal value of $K = 15.75$ was chosen to fill the whole possible entrance aperture of the C11 telescope ($K = 15.00$ for MASS/DIMM for TMT program). To provide both the adopted entrance plane location and the needed system magnification, the Fabry lens focal length and its position with respect to the exit plane can be adjusted moving the components of the LF unit. The exact value of the system magnification influences the final results of both MASS and DIMM because the geometry of entrance pupil is used in computation of the 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. 1.4. The coordinate system which is used here and further, is defined as follows:

– Z-axis goes 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 adjust the system magnification, which can differ from its nominal value due to lens focal length tolerance and uncertainties in the telescope geometry.

As we show in Optical design report [2], to avoid risk of too small or too large apertures, the two-elements Fabry lens is necessary, including negative and positive achromatic lens. Exact equivalent focal length of the system will be adjusted by alignment of inter-lens distance d. The dependence of equivalent focal length on d is shown on Fig. 1.2 for the chosen lens pair. Also, the separation between principal points is increased.

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. With adopted values ($K = 15.75$ and the telescope C11) outer diameter of the exit pupil is equal to 17.7±0.5 mm, inner diameter is equal to 6.4±0.2 mm, so the clear segment is 5.65±0.1 mm. The drawing of the exit pupil is shown in Fig. 1.3. The further

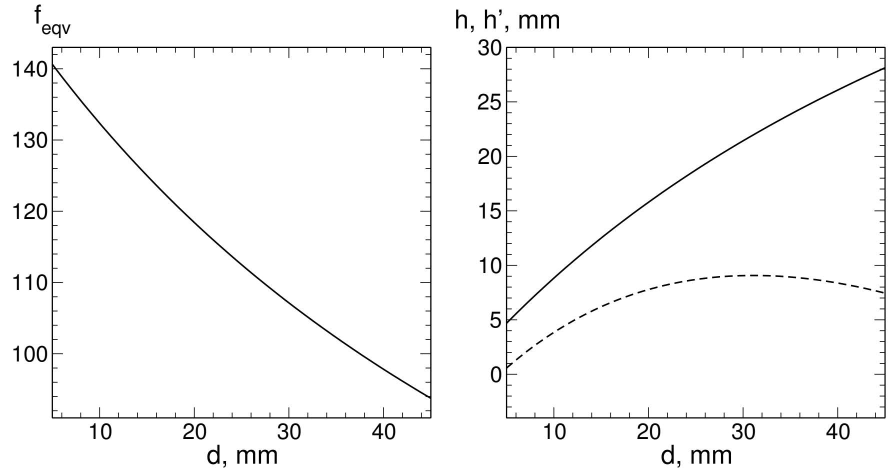

Figure 1.2: Dependence of the equivalent focal length of a complex Fabry lens (left) and position of principal points (solid — direct path, dashed — reverse) on the lens separation d

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 DIMM mirrors DM1 and DM2. Evidently, these elements must be within the exit pupil. In order to provide this, the lateral shifts of the exit pupil are foreseen in the design (see Sect. 2.2).

The presented numbers force to adopt the maximal outer diameter of the MASS pupil segmentation unit and maximal diameter of DIMM aperture as large as 5.50 ± 0.05, the same as in MASS-LITE and CTIO MASS/DIMM. For the case of a telescope with larger diameter, 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. 1.4 as ZY plane view, and in Fig. 1.5 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.

1.3.1 Pupil segmentation unit

The PSU is located off the instrument optical axis (see Fig. 1.3 and Fig. 1.5) at distance of 6.5 mm, 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

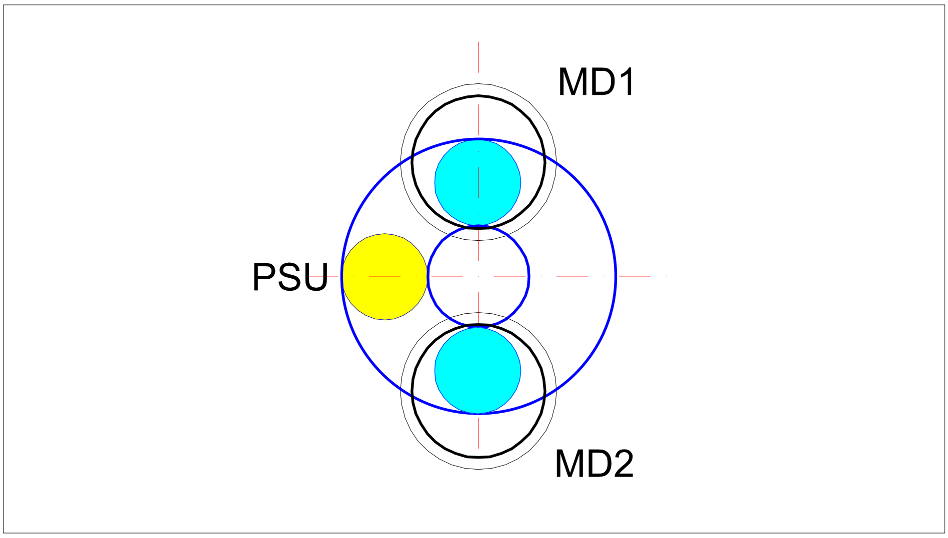

Figure 1.3: Geometry of exit pupil for telescope C11. MASS PSU is shown by yellow. DIMM masks are shown by cyan. Black — the placement of DIMM re-imaging mirrors.

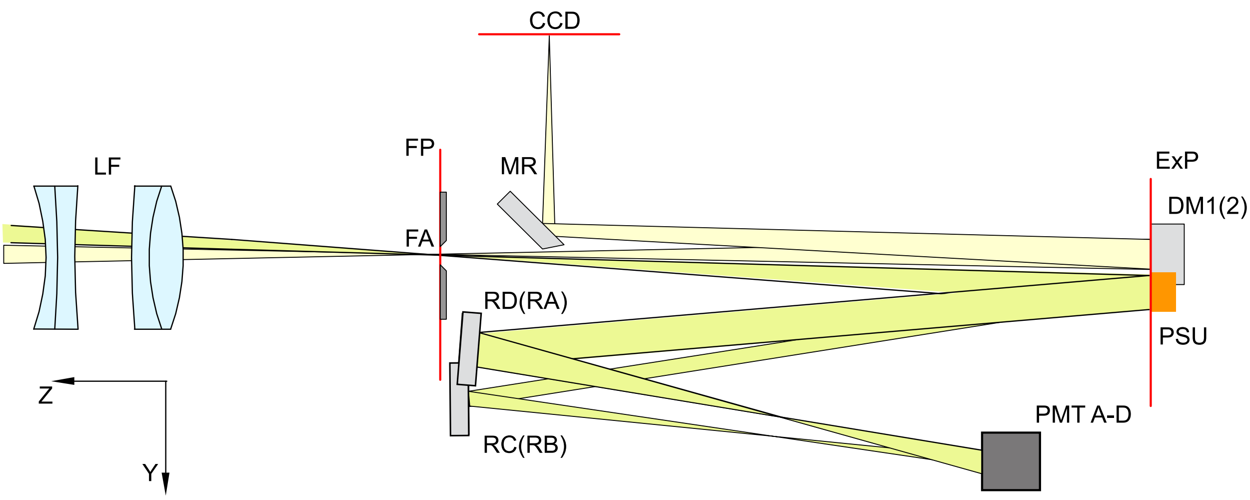

Figure 1.4: Optical layout of MASS/DIMM device in ZY plane. Common parts: LF — Fabry lens, FP — instrument focal plane, FA — field aperture, ExP — plane of exit pupil. MASS sub-device: PSU — pupil segmentation unit, RA, RB, RC, RD — re-imaging mirrors, PMTs — MASS detectors. DIMM sub-device: DMs — two DIMM re-imaging mirrors, MR — folding mirror, CCD — plane of CCD detector. Viewer is not shown.

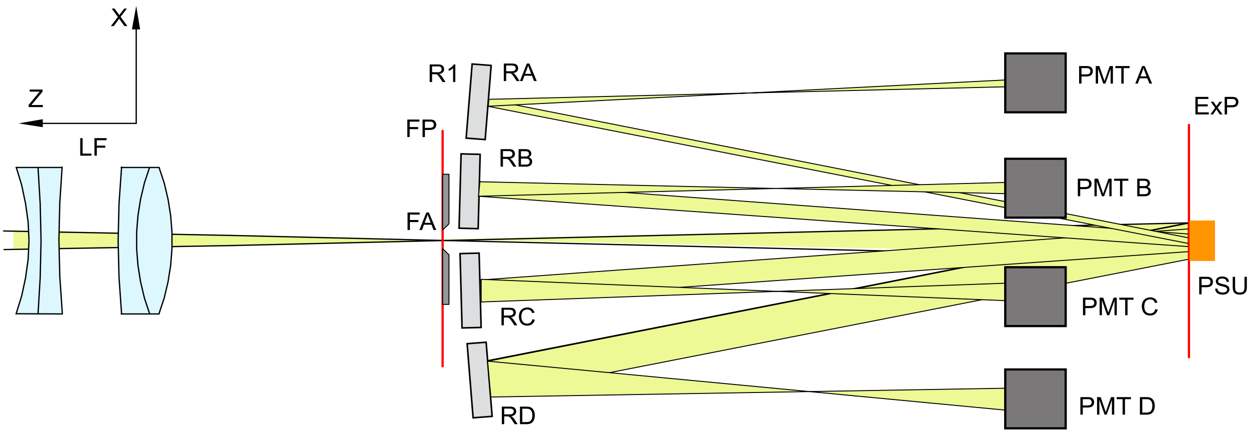

Figure 1.5: Optical layout of the MASS sub-device in ZX plane (corresponds to the bottom view in Fig 1.4). DIMM sub-device and viewer are not shown. Common part: LF — Fabry lens, FP — instrument focal plane, FA — field aperture, ExP — plane of exit pupil. MASS: PSU — pupil segmentation unit, RA, RB, RC, RD — re-imaging mirrors of the A-, B-, C-, and D-channels, PMT — four detectors.

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 [7] and geometry of exit pupil (see Sect. 1.2.3) the dimensions of the PSU segments were chosen as listed in [2].

Table 1.1: Measured PSU segment dimensions and entrance segments. All values are in millimeters

Segment/Channel	Physical diameter		Entrance diameter	
	inner	outer	inner	outer
Segment D	3.89	5.41	62.2	86.6
Segment C	2.19	3.86	35.0	61.8
Segment B	1.30	2.16	20.8	34.6
Segment A		1.27		20.3

Contrary to previous designs, the PSU is not fabricated from hard bronze but is replicated by A. Tokovinin, having applied right oriented bronze PSU as master and polystyrene for PSU replica. The replica is covered by Aluminum layer, and a protective *SiO* overcoating. The microphotograph of the PSU is shown in Fig. 1.6. Final diameters of PSU segments, measured

Figure 1.6: On the left: Side view of the one of the MASS segmentator mounted on its holder. On the right: Top view of the finished segmentator. The PSU is illuminated by scattered light.

with the help of such microphotographies for all produced segmentator, agree well (± 0.03 mm) with the nominal diameters, except outer diameter of segment D. Measurement shows that this real diameter is less by ≈ 0.1 mm than the nominal one. In the Table 1.1 the measured values are listed. Entrance segment diameters were calculated with $K = 16.0$ which is typical (and greater than nominal) for measurements during MASS/DIMM instruments commissioning in March 2006.

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.

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. Re-imaging mirrors are coated by protected Aluminum layer, reflecting up to 80%.

Re-imaging mirrors are tilted slightly to direct light to PMT photocathodes. 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 the diameter about 4.0 mm.

1.3.3 MASS spectral response

Spectral response of the MASS detectors affects the restoration of the vertical turbulence profile through weighting functions (see [12]), therefore the spectral response must be known well.

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.

We did not foresee the glass spectral filters to specify the short-wave cutoff of the MASS spectral response. The reason is to improve statistical accuracy in A and B channels where star flux is small.

The spectral response of MASS is shaped by the PMT spectral sensitivity at its red side, the transmittance of the optic parts at blue side (flint glass SF5 and lens and telescope optics visual anti-reflection coating, mainly). The final spectral response is shown in Fig. 1.7 (right) and numerical data are presented in the Table 1.2. Such spectral response produces a dependence of MASS magnitude on star color. In Fig. 1.7 (left) the dependence is plotted. Transformation from standard V magnitude is described as follows:

$$MASS = V + 0.71(B - V) - 0.091(B - V)^2$$

This equation may be used for control of the MASS spectral response. Such control is needed because the transmittance of the telescope entrance correction plate is not well known.

Table 1.2: MASS spectral response in relative photon units. Wavelengths in nanometers

λ	$S(\lambda)$	λ	$S(\lambda)$	λ	$S(\lambda)$	λ	$S(\lambda)$
330	0.010	410	0.720	490	0.920	570	0.255
340	0.020	420	0.830	500	0.830	580	0.203
350	0.050	430	0.890	510	0.740	590	0.160
360	0.100	440	0.950	520	0.640	600	0.125
370	0.170	450	0.990	530	0.550	610	0.090
380	0.280	460	1.000	540	0.472	620	0.070
390	0.430	470	1.000	550	0.397	630	0.050
400	0.580	480	0.970	560	0.320	640	0.040

The integral parameters of the MASS spectral response are: effective wavelength λ_{eff} for A0 star 467 nm (496 nm for TMT instruments with cutoff filter), spectral bandwidth $\Delta\lambda_{1/2}$ about 100 nm (85 nm). Effective wavelength for other star can be approximated by dependence $\lambda_{eff} = 467 + 29 \cdot (B - V)$. So, the ELT MASS spectral response mimics rather the B photometric band than V.

More precise control of the MASS spectral sensitivity requires the carefully prepared star list, since:

- some program stars have variability $\approx 0^m.05 \div 0^m.1$. For example μ1 Sco have amplitude $\approx 0^m.3$.
- a slope of $(V_{MASS} - V)$ versus $(B - V)$ color depends on effective wavelength mainly, a curvature of this one depends on width of the spectral band, so not only blue and red stars must be measured, but uniformly distributed over color range.

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

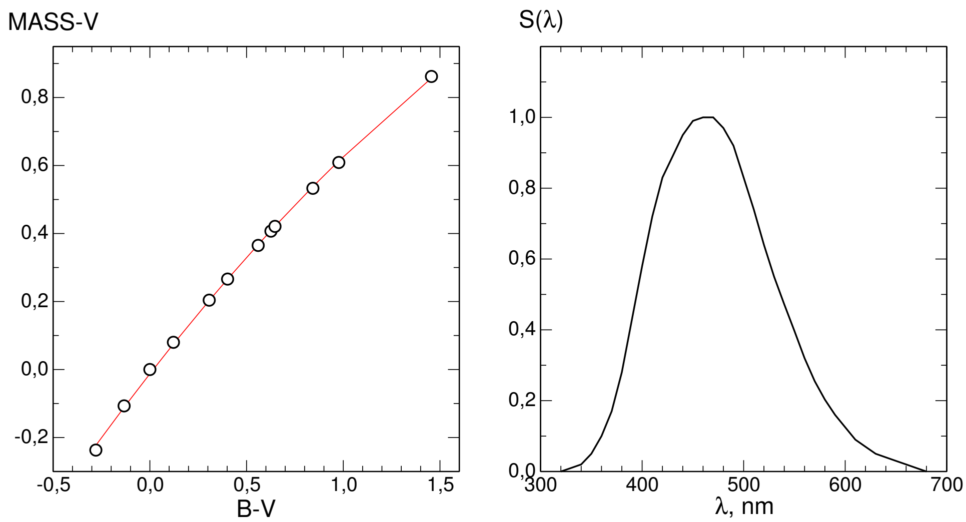

Figure 1.7: On left: Color equation between MASS magnitude and star color index B-V. On right: Spectral response of the ELT MASS device.

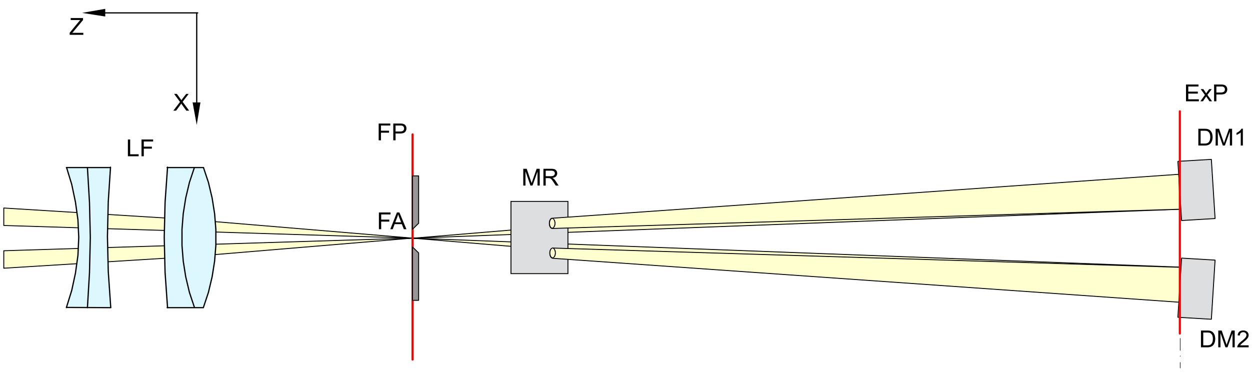

Figure 1.8: Optical layout of DIMM sub-device in ZX plane (corresponds to the top view in Fig 1.4). The MASS sub-device and viewer are not shown. Common part: LF — Fabry lens, FP — instrument focal plane, FA — field aperture, ExP — plane of exit pupil and mask. DIMM: DM1 and DM2 — DIMM re-imaging mirrors, MR — folding mirror.

CCD detector surface. The distance between the mask holes defines the DIMM base (see Fig. 1.4 and Fig. 1.8).

The diameter of the re-imaging mirror is equal to 10.8 mm with clear diameter 9.8 mm (see Fig. 1.3). Such a diameter permits to fix the DIMM base with 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.

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 1.3. The physical dimensions are determined by fabricated mask, entrance dimension are calculated for the case of $K = 16.0$.

Table 1.3: DIMM channel basic characteristics. All values are presented in millimeters

Segment/Channel	Physical dimension	Entrance dimension
Diameter of aperture	5.5	88
Base b_D	12.1	194
Scale on CCD		$88 \pm 5''$/mm

The distance between the DIMM mirrors and the folding mirror MR (see Fig. 1.8) is 100 mm. 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 change slowly due to abberations as well. In the plane XZ, the DIMM mirrors are tilted by ±3.19° . Note, 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. On the other hand, the aperture limits the field of view for DIMM sub-device. As a compromise, the 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 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 must be done by the DIMM software.

The viewer is not used in a normal work since the DIMM sub-device provides the star detection after telescope was pointed at the star and guiding during measurements. In practice, the viewer serves as an auxiliary tool in extraordinary cases.

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 with focal length 50 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 and telescope and about 40 mm from the back plane of telescope to provide easy access for the observer.

Chapter 2

Mechanical design

2.1 General description

Mechanical design of the combined MASS/DIMM device is done on the base of CTIO and TMT MASS/DIMM development. We keep the main dimensions and general structure of the device. But a number of units were redesigned to provide matching with Celestron 11 telescope. Also, some modifications were implemented if previous design was found not optimal. External view of the ELT MASS/DIMM instrument is shown in Fig. 1.1 attached to Celestron 11 telescope.

Practically all parts of the device are fabricated from hard aluminum alloy, black-anodized. Only few critical parts are made from stainless steel. The dimensions of the instrument and its weight are minimized. The full length of the device is 175 mm. The width and depth of the device without a viewer tube and CCD camera is about 80 mm $\times$ 90 mm. The eyepiece of the viewer is 165 mm apart from the device side. Total weight of the MASS/DIMM instrument is about 1.5 Kg.

The instrument is fixed on the feeding reflector instead of a 2 inch Back focus barrel with help of a thread on the special mount ring **02A**. Main box can be aligned with respect to this ring with four pairs of pop-pushing screws **PP2**, to provide the needed position of the telescope exit pupil on segmentator unit. The needed positional angle of the device is fixed by the counter-blocking screw. At the device front side **01A**, the Fabry lens unit **02** is attached.

The side cover **01B** of the MASS device box is detachable for access to the optics of the instrument fixed on the transversal beam **01E** which is called hereafter “optical bench”. This bench bears the field diaphragm **FA**, the removable mirror **MV** and the glass **CC** with the centering hole of the viewer, the main blind **06C** and four re-imaging mirrors **RA - RD**. The bench with the optics may be detached from the device if needed. No additional adjustment is expected after back mounting of the bench on the device.

In particular, the removal of the optical bench is needed for the focusing of the Fabry lens to allow the easy access to its rotating holder and to reduce the large depth of sharpness caused by the small field diaphragm size. After bench removal, the segmentator may be illuminated with a small lamp and its image may be investigated and measured in the entrance pupil plane.

The pupil segmentation unit is mounted in the socket of the bottom tie **01D** of the device box. PSU may be removed and fixed back for checking or cleaning. The special cover **01F** allows an access to the fixing and adjustment screws of the PSU.

In the MASS channel (sub-device), the light reflected from PSU and then from re-imaging

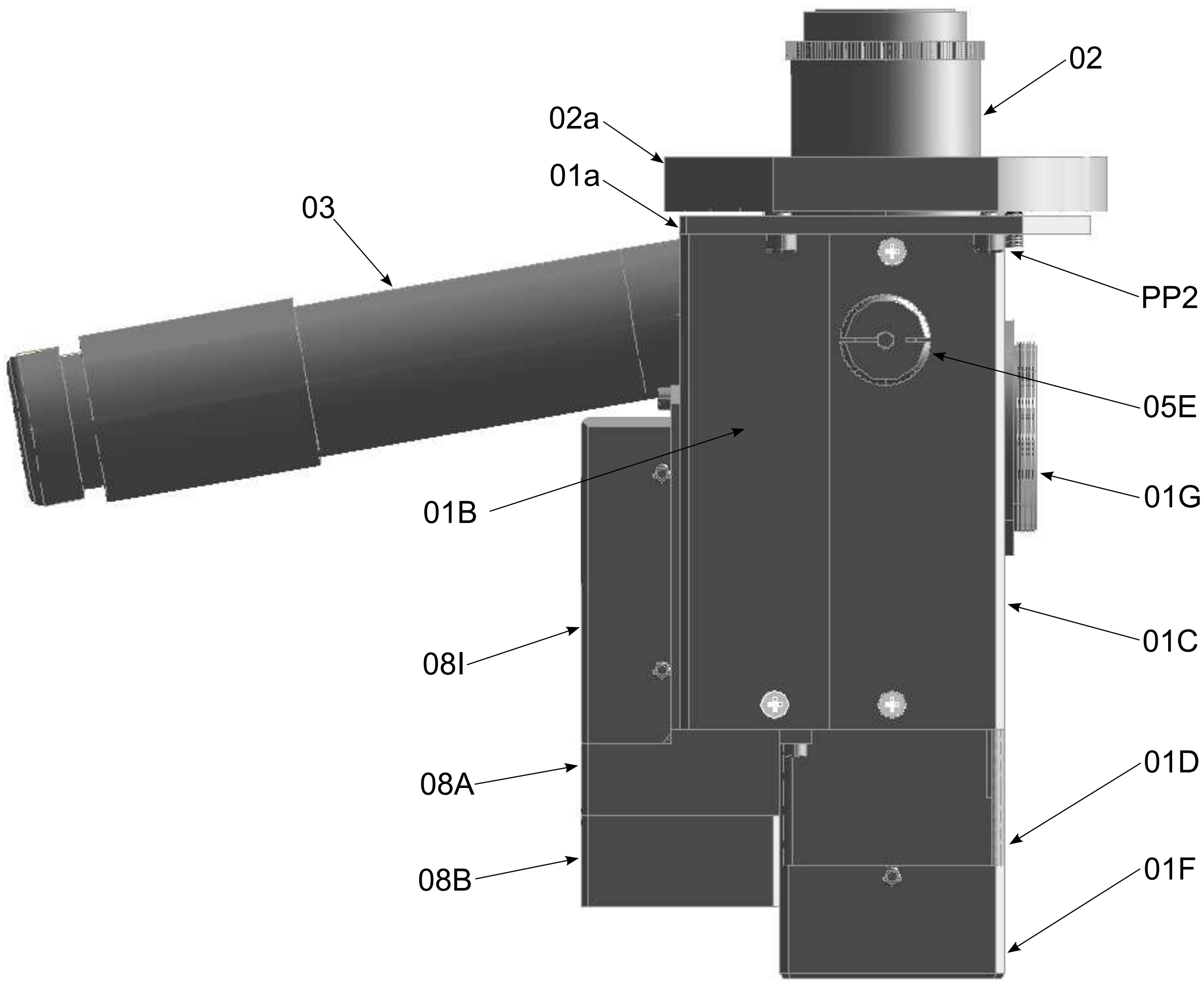

Figure 2.1: Side view of the MASS/DIMM device without CCD camera. See designations in text.

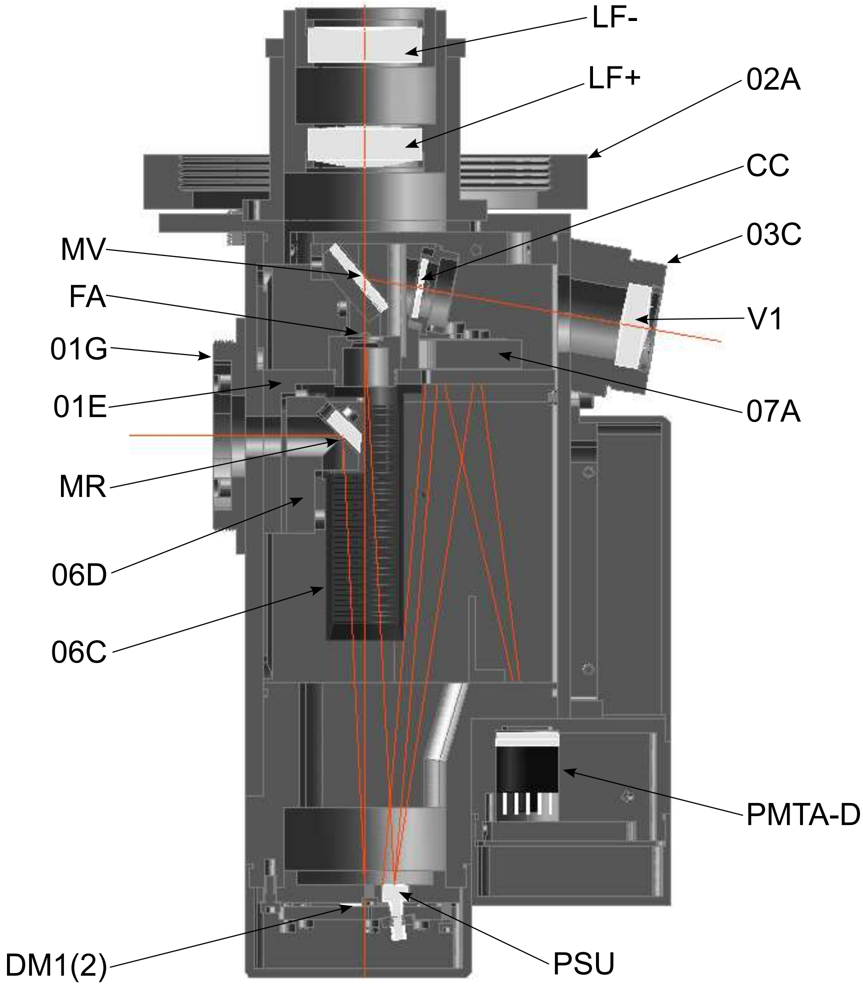

Figure 2.2: Cross-section view of the MASS/DIMM device.

mirrors falls onto photomultipliers **PMT**. In the DIMM channel, the light beam is reflected by mirror **MR** and arrives onto the CCD detector plane.

In order to remove the side cover of the device, the electronic and photometric unit **08** must be first unscrewed and removed as one box. The viewer **03** with Kellner type eyepiece can be removed for robotic observations.

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

In Fig. 2.1 the general view of the device is shown. The cross-section of the device is presented in Fig. 2.2 to explain its interior design.

2.1.1 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. This structure bears all other units and assemblies. Do not disassemble the device skeleton unless there is no other solution! Device base holds the Fabry lens unit **02** and is screwed to mount ring **02A**.

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 **01G** is fastened. Also, the switching knob of the viewer mirror, **05E**, is placed at one side of the beam.

The optical plate with PSU and DIMM re-imaging mirrors DM1 and DM2 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, PMTs blind **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.

2.1.2 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:

- 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. 2.3. In this pictures, 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. Two push screws **PP5** permit to adjust a little the total tilt of the mirrors holder.

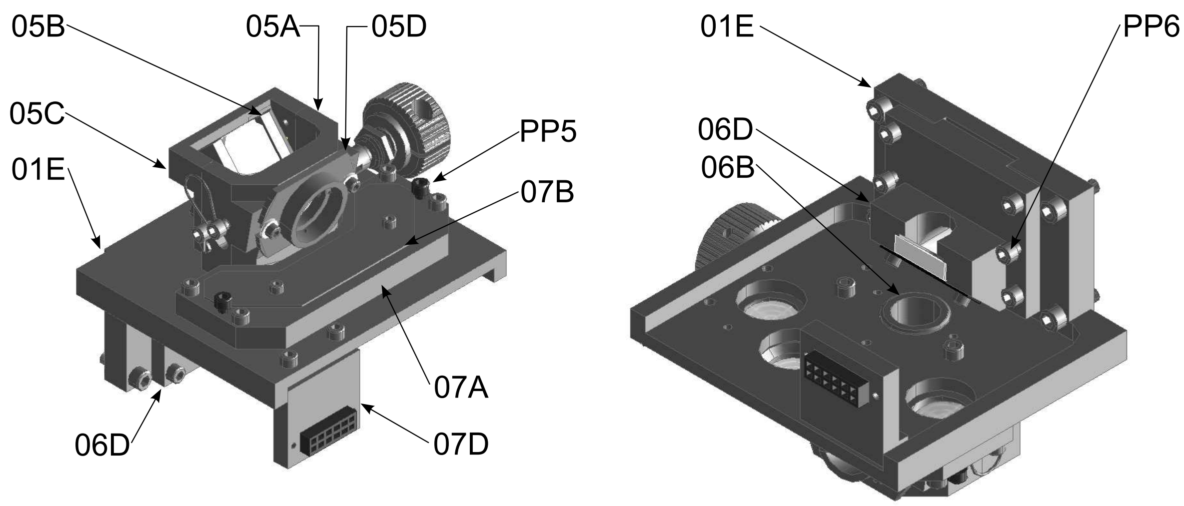

Figure 2.3: The top (left) and bottom (right) views of the optical bench.

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 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 **PP6** 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 in the Document [8]. In addition to the above-mentioned electronics, two control light LED PCB is mounted to the bench directly.

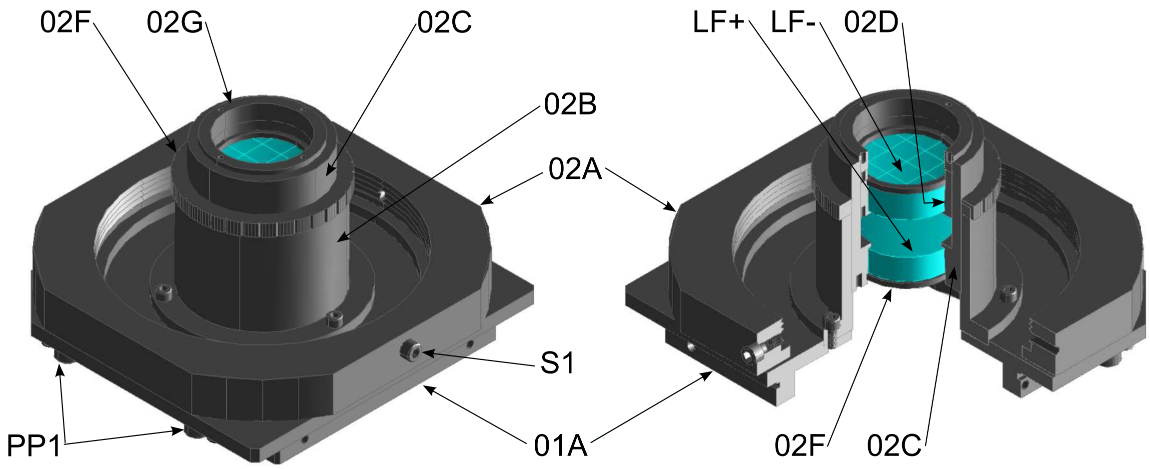

Figure 2.4: The view of the complex Fabry lens unit

2.1.3 Fabry lens unit

The Fabry lens unit is superimposed with mechanism, providing MASS/DIMM device tilt with respect to optical axis of the feeding telescope. The Fabry lens unit itself includes the tube **02B** with a thread for the positive lens holder **02C**. The thread serves to focus the Fabry lens. The negative lens is installed in the holder **02D** which is able to move respectively **02C** by thread again. This permits to change distance between lenses and varies the equivalent focal length of the complex Fabry lens.

Optical elements are mounted in their holders with using a thin locking nut **02E**. After focus alignment, to fix the lenses position the lock nuts **02G** and **02F** are used.

2.1.4 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. After viewer removing, the viewer flange must be close by special cap **03E** to prevent light and dust pollution.

2.1.5 Optical plate

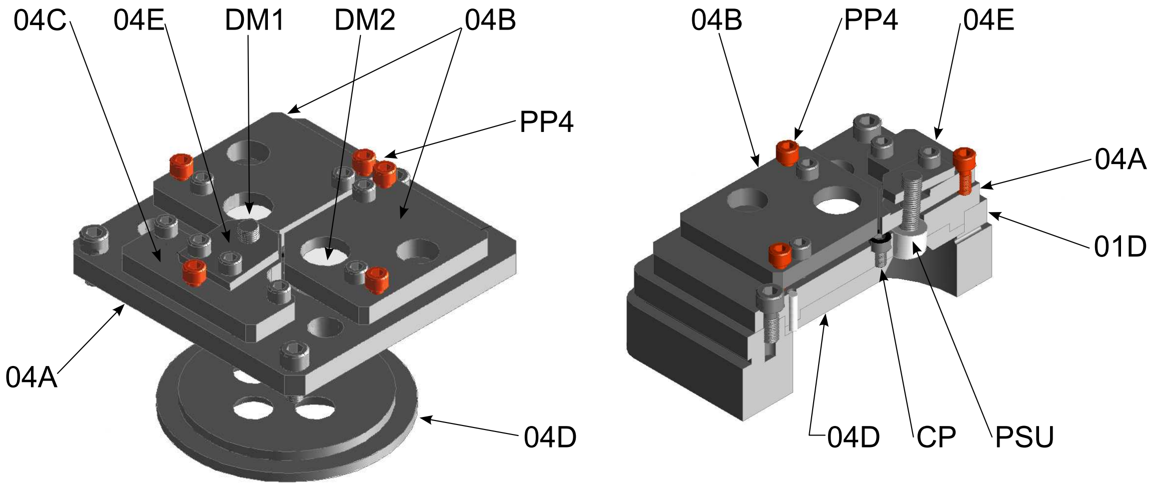

Figure 2.5: The view of the optical plate with PSU holder and two DIMM mirrors alignment plane.

The optical plate **04A** and other parts related to this unit are fabricated from stainless steel to provide stability of the alignments for PSU and DIMM re-imaging mirrors. The external views of the plate are shown in Fig. 2.5. In the center of the plate a low central pad **CP** (height ≈ 1 mm) is placed. All three adjustable parts are pressed against this pad on one end.

The PSU holder **04C** is fastened by 3 screws — 2 pulled and 1 pushed. The PSU itself is installed in thread hole of the holder by PSU foot and locked by 2 screws with help of locking plate **04E**. When unlocking, PSU has a freedom to rotate around its axis.

The DIMM mirror plates (right and left) **04B** are mounted by 4 screws, 2 pulled and 2 pushed. The DIMM mirrors are cemented in the sockets of the mirror plates.

From the opposite side of optical plate, a MASS/DIMM mask **04D** that defines the exact geometry of the exit pupil is inserted. Right angular position is provided by special pin pressed in the optical plate. This permits the optic plate to be removed from the MASS/DIMM device either with the mask or without it. In the latter case, the mask must be fixed to the bottom tie with help of 2 screws. For these screws, the four holes in the plate are foreseen.

The optical plate is mounted in the socket of the bottom tie of the device box. The special cover protects the optical plate and its fixing and alignment screws.

2.1.6 Electronics module design

The electronics module (see Fig. 2.6) 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.

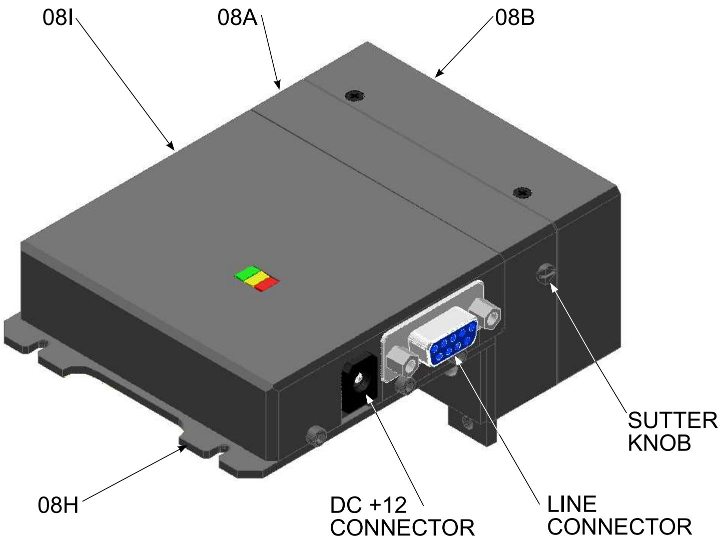

Figure 2.6: View of the detached electronics module.

The shutter mechanism (inside PMTs housing) consists of two steel blades with holes, a cramp, a lever, and the axis **08G – Shutter knob**. The axis passes through the hole in the housing, its rotation closes (clockwise) or opens (counterclockwise) the shutter. The shutter 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. All the alignments must be performed when the telescope is focused at infinity.

The alignments are:

- focusing of the Fabry lens;
- lateral shifts of the exit pupil with respect to segmentator;

– 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 **02C** in the thread of the support tube **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 (half a turn) is more than sufficient. The full range of focusing of ± 10 mm around the nominal position is provided. The nominal Fabry lens position depends on the particular feeding telescope. Do not forget to fix the final position with help of the lock ring **02F**.

To set the correct magnification factor (usually, the maximal possible for current telescope) the focal length of the LF can be adjusted. For this, remove lock nut **02G** and rotate the negative lens holder **02D** with respect to positive lens holder. Remember, that if you twist out holder, the distance between lenses is enlarged and equivalent focal length is decreased (see Fig. 1.2). As result, the magnification K increases. In this case, the size of exit pupil, inspected with additional focusing tool, will decrease. Also, fix the holder by lock nut **02G** and repeat the focus procedure.

The coincidence of the image of instrument exit pupil and complex segmentator is achieved by tilt of the whole device with respect of the mount ring **02A**. Three pair pop-pushing screws **PP2** permit to provide needed position with of accuracy of about 0.1 mm. Forth pair is used for final fixing.

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.

2.2.2 MASS sub-device optics

After the MASS segmentator is fixed in its place, the PSU position angle should be tuned to correct value and the segmentator should be 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. These alignments are provided by the push-and-fix screw pairs having the full range of about $\pm 1.5°$ (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 $\pm 0.2°$ (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 $\pm 1°$ is sufficient. Use PP7 screws for this.

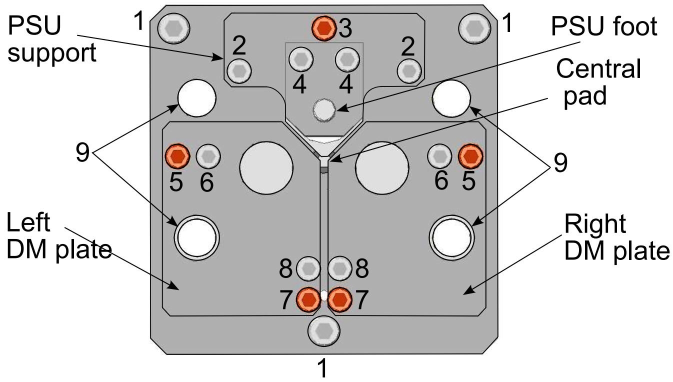

Figure 2.7: The optical plate with PSU in its holder and two DIMM mirrors alignment plates. 1 — screws M2.5 fixed plate to device, 2 — pull alignment screws M2 of the PSU support, 3 — push screw M2 for PSU tilt alignment, 4 — PSU lock screws, 5, 6 — push and pull screws M2 for alignment of the DIMM mirrors tilt in X direction, 7, 8 — push and pull screws M2 for alignment of the DIMM mirrors tilt in Y direction, 9 — windows for mask fixing screws.

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 $\pm 1^\circ$ range which covers ± 3 mm range on the CCD (see Fig. 2.7).

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 support tube 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 special 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. 2.7) completely, support the plate by hand. If you wish to remove the mask too, before unscrew 2 M2 screws which hold the mask in bottom tie socket.

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 internal side of the main beam, unscrew completely 4 screws which are around the folding mirror support **06D**. 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 negative lens of the complex 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

Since the MASS PSU in ELT MASS/DIMM is a monolithic element, the alignment of the separate segments is not required. PSU alignment includes tuning position angle of segmentator around its rotation axis and tilts in X and Y direction.

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 PSU orientation will direct the beams onto the mirror centers. After finishing the tuning of rotation angle, tighten the PSU lock 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 3 on Fig. 2.7). 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.

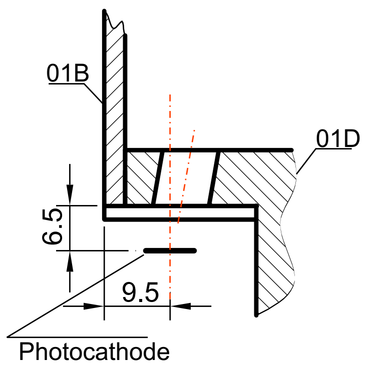

Figure 3.1: Photocathodes position with respect to the reference plate of the bottom tie.

Pay 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 5, 6, 7 and 8 at the optical plate (see Fig. 2.7), put the images built by right DM1 and left DM2 re-imaging mirrors into the center of CCD detector.

This images must be separated at about 50 pixels symmetrically with respect to the frame center. 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.

If CCD camera has its own focus possibility — focus the camera to provide sharp image of field aperture edge. The test picture of the field aperture is shown in the Fig. 3.2 on left. The separation is bigger than nominal — about 100 pixels.

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.

During this stage you can adjust a separation between "star" images. Do not mix up the right and left image! If you are not sure where is the right and left image in CCD frame — change slowly the CCD camera focus. When images are set correctly, the approach of the camera to device produces enlarging of the images separation.

If you detect that images are mixed up, transpose them with help of alignment screws No 5, 6, 7 and 8 at the optical plate. See the Fig. 3.2.

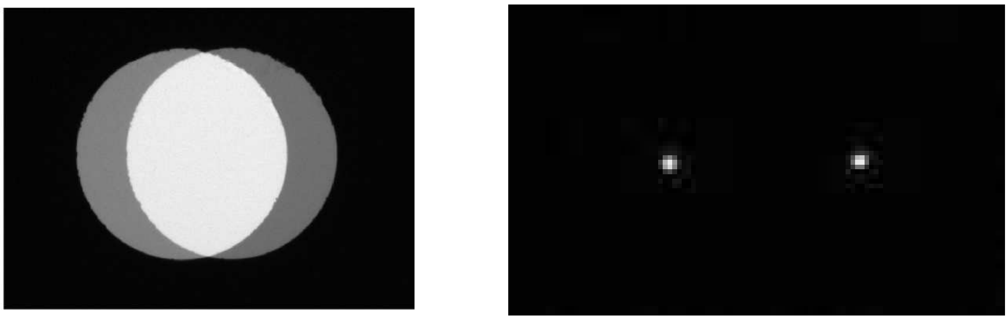

Figure 3.2: On left: The CCD frame of the illuminated field aperture. On right: Right aligned artifical star images with the horizontal separation of 41 pixels.

The described alignments are normally done in the laboratory once after the device optics assembly but it is useful to check this alignments at the telescope, too. 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 special tool (Fig. 3.3) delivered with MASS/DIMM instrument. This tool represents a wide-field eye-piece designed to install on the device instead the optical plate **04A**. In first, remove optical plate. To do this, unscrew the screws No 1. Then, with care, separate it from bottom tie using thin screwdriver. Mask **04D** must be rest on the place because it is fixed by 2 screws to the bottom tie **01D**. Install wide-field eye-piece, focus it to mask edges.

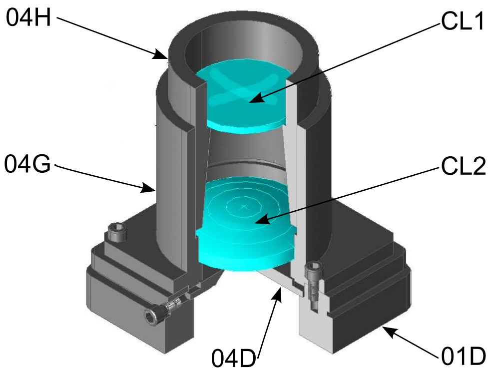

Figure 3.3: Wide field eye-piece for exit pupil alignments.

Then, remove the side cover **01B** and optical bench **01E**. Illuminate well the entrance aperture of the telescope or point telescope to the bright object such as a white wall. The image of the telescope entrance pupil can be viewed directly through the mask with help of WF eye-piece. Tilting device by push-pull screws **PP1** put this image symmetrically with respect to mask holes. Be sure that the telescope is preliminary focused at infinity.

Place some flat opaque object with a sharp edge (e.g. a paper stripe or a ruler) into the plane of the entrance pupil (top end of the telescope tube). Observe the image of this object in the plane of exit pupil. If the Fabry lens is correctly focused, the pupil image with an object shadow will be seen sharply. Otherwise, Fabry lens focusing must be performed.

The simplest way to do this is to remove MASS/DIMM from the telescope after marking its adopted position angle. Spin out LF holder at 2 revolutions. Install the device on the telescope again. Check sharpness and repeat focus procedure if needed. In practice, such procedure converges quickly.

When the correct LF focusing will be reached, the image of the telescope entrance pupil may appear less or greater than mask. One can see inner or outer vignetting of MASS or DIMM apertures. In this case alignment of the instrument magnification must be done.

To set the correct magnification factor (usually, the maximal possible for a given telescope), the focal length of the LF can be adjusted. For this, remove the lock nut **02G** and rotate the negative lens holder **02D** with respect to the positive lens holder. Remember, that if you twist out holder, the distance between lenses is enlarged and equivalent focal length is decreased (see Fig. 1.2). As a result, the magnification K increases. In this case, the size of exit pupil, inspected with additional focusing tool, will decrease. Also, fix the holder by lock nut **02G** and repeat the focus procedure.

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

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

Point telescope to some star. Doubled star image must appear in the CCD frame. Focus the telescope and correct the telescope pointing to provide the images in the center of the CCD frame. If needed, 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. It is very convenient to do this just after focusing Fabry lens while optical plate **04A** is removed and wide-field tool is installed at the device bottom tie.

Remove the top (ocular) part **04H** of the tool. Put some strong light source in front of the field lens **CL2**.

The mask **04D** image is built in the entrance pupil plane of the MASS/DIMM + telescope system. Place some semi-transparent screen (paper sheet) 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 images of all three holes in mask (MASS and 2 DIMM). Measure the diameter of these holes and distance between DIMM aperture with help of any ruler or mark the hole edges for further measurement.

While examining the edges of these mask holes, make sure that there is no vignetting in the system (edges are equally sharp, vertical size is equal to the horizontal size).

The magnification of the system is obtained by division of the measured sizes by the corresponding physical diameters of the mask **04D** holes (see Table 1.1). 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. The real scale may differ from the preliminary value (see Table 1.3). Determination of DIMM CCD scale must be done after the all device alignments are finished and feeding telescope is focused precisely.

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 weak 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.

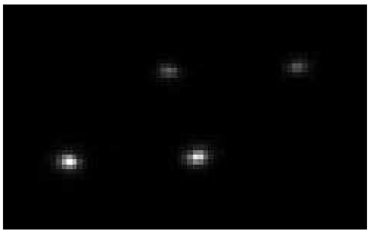

Figure 4.1: CCD image of the binary star HR8895 obtained for scale determination.

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 [13]). 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.

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

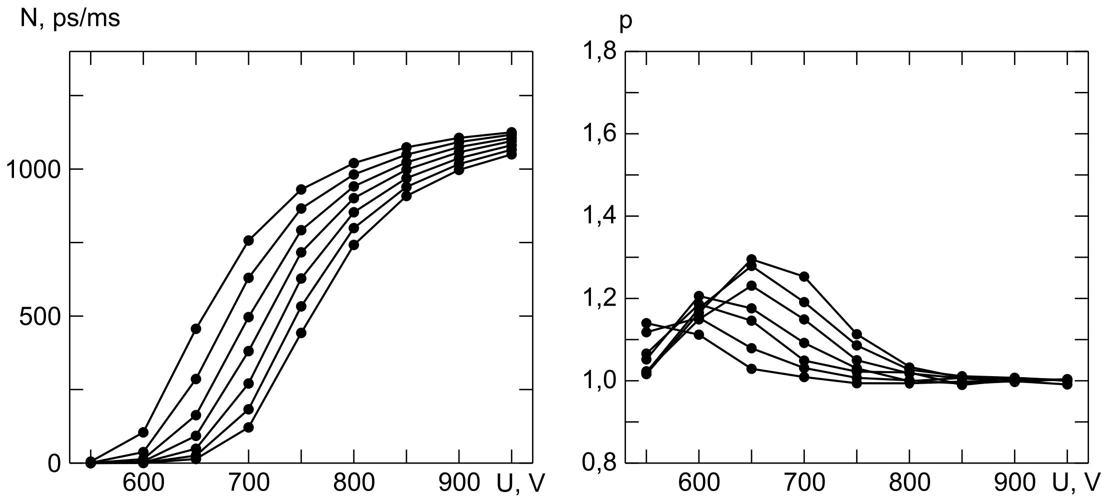

Figure 4.2: Light counting functions. Left: Flux dependence on the high voltage for 7 threshold levels (0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9 mV), lowest curve corresponds to the 0.9 mV level. Right: Non-Poisson parameter as a function of Voltage for 7 threshold levels, here lowest curve corresponds to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

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 not be 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).

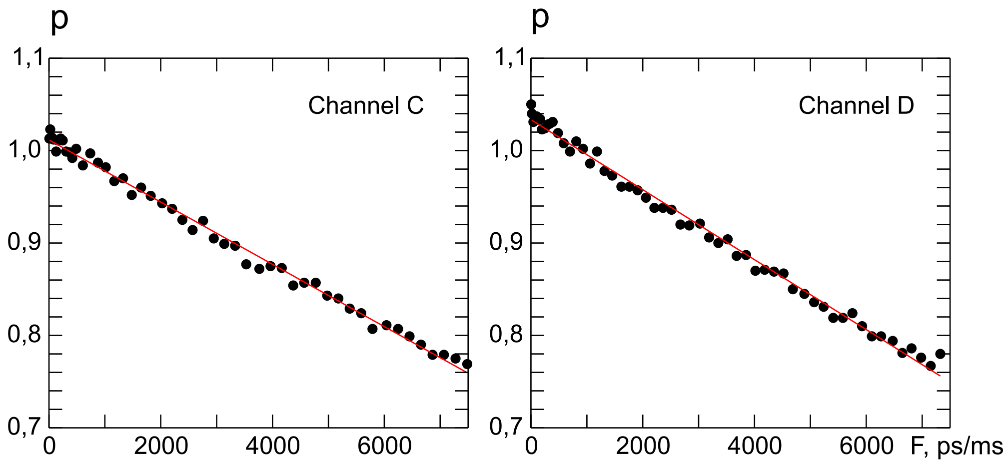

Figure 4.3: Dependence of non-Poisson parameter p on flux F for C and D channels. Line is linearly fitting the measured points.

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 C and D 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 -2τ 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 16 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.
1	**Fabry lens 1** Focal length: -150 mm Diameter: $25.0^{+0.0}_{-0.2}$ mm	Edmund Optics	ACH25x-150MgF2 TS NT45-423	4	1
2	**Fabry lens 2** Focal length: 75 mm Diameter: $25.0^{+0.0}_{-0.2}$ mm	Edmund Optics	ACH25x75MgF2 TS NT32-325	4	1
3	**Viewer lenses** Focal length: 50 mm Diameter: 18 mm	Edmund Optics	ACH18x50MgF2 TS NT32-913	8	1
4	**Control lenses 1** Focal length: 75 mm Diameter: 30 mm	Edmund Optics	PCX30x75MgF2 TS NT32-486	4	1
5	**Control lenses 2** Focal length: 40 mm Diameter: 25 mm	Edmund Optics	PCX25x40MgF2 TS NTNT45-279	4	1
6	**Kellner eyepiece** Focal length: 12 mm Barrel diameter: $1\frac{1}{4}$ inches	Any	—	4	

1. 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	8	1
	Size: 12×18 mm				
	Substrate: BK7 glass				
	Thickness: 2 mm				
	Surface Accuracy: $\lambda/4$				2
MR	**DIMM folding mirror**	OP3	op3.dwg	8	1
	Size: 10×15 mm				
	Substrate: BK7 glass				
	Thickness: 3 mm				
	Surface Accuracy: $\lambda/10$				2
R1-4	**MASS mirrors**	OP1	op1.dwg	32	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	16	1
	Diameter: 10.8 mm				
	Curvature radius: 136 mm				
	Substrate: BK7 glass				
	Thickness: 5 mm				
	Surface Accuracy: $\lambda/10$				2
PSU	**Segmentator**		md10a.dwg	8	1
	Diameters: see Tab. 1.1		md10b.dwg		
	Curvature radius: 250 mm		md10c.dwg		
	Substrate Material: Plastic replica		md10d.dwg		
	Surface Accuracy: $\lambda/4$				2
CC	**Circle reticle**	OP6	op6.dwg	9	3
	Central hole 1.2 mm				
	Thickness: 1.0 mm				
	Diameter: $13.0^{+0.0}_{-0.2}$ mm				

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

The table 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. The list contains 57 parts. Needed fasteners and standard items are not included in this table and will be presented separately.

Des.	Part	Material	Q-ty	Rem.
ME01	**Box**			
ME01A	Device base	HA	1	C
ME01B	Box cover	HA	1	S
ME01C	Main beam	HA	1	C
ME01D	Bottom tie	HA	1	C
ME01E	Optics bench	HA	1	C
ME01F	Segmentator cover	HA	1	S
ME01G	CCD camera interface	HA	1	S
ME02	**Fabry lens unit**			
ME02A	Mount ring	HA	1	R
ME02B	Fabry lens tube	HA	1	R
ME02C	Positive lens holder	HA	1	R
ME02D	Negative lens holder	HA	1	R
ME02E	Locking nut #1	HA	2	R
ME02F	Fixing nut #1	HA	1	R
ME02G	Fixing nut #2	HA	1	R
ME03	**Viewer**			
ME03A	Eyepiece socket	HA	1	R
ME03B	Viewer tube	HA	1	R
ME03C	Viewer socket	HA	1	R
ME03D	Locking nut #2	HA	2	R
ME03E	Viewer cup	HA	1	R

Des.	Part	Material	Q-ty	Rem.
ME04	**Pupil segmentation unit**			
ME04A	PSU support	Steel	1	C
ME04B	DIMM mirror plates	Steel	2	C
ME04C	MASS segmentator holder	Steel	1	S
ME04D	Aperture mask	HA	1	S
ME04E	PSU locking plate	Steel	1	S
ME04F	Pupil control tool #1	HA	1	R
ME04G	Pupil control tool #2	HA	1	R
ME05	**Switching mirror unit**			
ME05A	Support	HA	1	C
ME05B	Mirror holder	HA	1	C
ME05C	Clamping cramp	HA	1	S
ME05D	Illuminators plate	HA	1	R
ME05E	Right axis	Steel	1	R
ME05F	Knob axis	Steel	1	R
ME05G	Switching knob	HA	1	R
ME05H	Bushing	Steel	1	S
ME05I	Bushing nut	Steel	1	S
ME05J	Left axis	Steel	1	R
ME05J	Left axis	Steel	1	R
ME05K	switch spring	Steel	1	R
ME06	**Central unit**			
ME06A	Field aperture	Steel	1	R
ME06B	Aperture support	HA	1	R
ME06C	Central blind	HA	1	R
ME06D	Folding mirror support	HA	1	C
ME06E	Spring cover plate	Steel	1	S
ME07	**Other parts**			
MD07A	MASS mirrors socket	HA	1	C
MD07B	Mirrors cover plater	HA	1	S
MD07C	PMTs side blind	HA	1	S
MD07D	Connector support	HA	1	S

Des.	Part	Material	Q-ty	Rem.
ME08	**Electronics box**			
MD08A	PMT house	HA	1	C
MD08B	Detectors cover	HA	1	S
MD08C	PMT separator	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	HA	1	S
MD08J	DB9 support	HA	1	S