Matching MASS-DIMM to Meade RCX-400 telescope

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1 Introduction

Site monitors with MASS-DIMMs at Cerro Tololo, Cerro Pachón and other observatories use cheap Meade telescopes LX-200 (25cm diameter) as feeding optics. The focusing and pointing of these telescopes is not stable owing to the motion of the primary mirror inside the tube and to the thermal expansion of the tube.

New telescopes of RCX-400 series from Meade are promising as feeding optics for MASS-DIMMs. They have tube of carbon fiber (much smaller thermal expansion) and computer control of focus and alignment by moving the meniscus (with the secondary mirror attached to it). The primary mirror is firmly fixed (glued) in the tube. This should ensure a stable pointing. See Sky & Telescope, May 2005, p. 86.

The RCX-400 telescopes have a wide corrected field owing to the new optical design (Murdock, analogue of Richey-Cretien). At the same time they have a faster focal ratio $f/8$ (compared to $f/10$ in LX-200 telescopes). Considering that the 25-cm pupil of LX-200 fits the MASS-DIMM pupil geometry very tightly, and that RCX-400 has a larger central obstruction, we opted for a larger aperture and selected the RCX-400 telescope of 12" (305mm). Its nominal focal length of 2438 mm is a good match to MASS-DIMM.

2 Telescope parameters

Optical parameters of the telescope are not provided by the Meade company. Thus, we had to establish them by reverse engineering. By measurements we established that the nominal distance between M1 and M2 is about 400mm (with uncertainty of 10mm). The distance from the M1 surface to the back flange (the piece with 83mm thread) is about 100mm. Finally, the distance from that flange to nominal focus is about 200mm (measured on Meade accessories). Taking M1-M2 and M2-focus distances as parameters, we calculate an optical system with 2 spherical mirrors that has nominal focal length of 2438mm, using Zemax. Then we adjusted the two conic constants (CC) for correcting spherical aberration and the field. However, further study of this "equivalent Richey-Cretien" showed that it does not match the actual optical performance when combined with the MASS-DIMM. So, we specified the spherical primary and adjusted the aspheric term on the meniscus ($\propto x^4$) and the CC of the secondary. This provides an approximation to the actual Murdock optical design of RCX-400.

The resulting optical prescription of 12" RCX-400 is given in Table 1. In this telescope, the exit pupil of 112mm diameter is located at 895mm in front of the focus (695mm from the flange). The meniscus (assumed BK7 glass) has a 4-th order Zernike term, $z = -2.698\ 10^{-10} r^4$ on its front surface. The prescription is, of course, not exact, but it is deemed to be a reasonable "proxy" of the real RCX-400.

Table 1: Approximate optical prescription of RCX-400 (rx400c.zmx)

Element	R, mm	CC	Dist. to next, mm
Meniscus (10mm, BK7)	INF	-	450
Primary mirror M1	-1122	0	-400
Secondary mirror M3	-418.2	-0.937	500
Back flange	INF	-	200
Focal plane	-188	-	0

3 Matching RCX-400 to MASS-DIMM optically

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In the standard MASS-DIMM, a single Fabry lens in front of the focus (at some 30mm) produces the pupil image at a distance of 123mm behind the focus. At the same time the lens modifies the f-ratio, making the beam faster. However, the final f-ratio (hence plate scale) at the CCD is partially restored by the re-imaging mirrors of the DIMM channel (nominal magnification factor 1.236).

We placed the MASS-DIMM with its nominal Fabry lens ($f = 125$mm) at the output flange of RCX-400. The axial position of the lens that corresponds to focused pupil was found to be 31mm in front of the focus (to the back of the lens). The diameter of the pupil image was measured at 24 $\pm$ 0.1 mm. Knowing the parameters of the Fabry lens, we estimate the exit pupil position at some 600mm in front of the lens.

The resulting magnification factor of the pupil is $350/24 = 12.7$. With such magnification, the 5.5mm outer segment of MASS will be projected to 70mm on the pupil. This is smaller than the current diameter of 80mm.

It will be possible to use RCX-400 with the same Fabry lens if another, larger segmentator is manufactured. This option requires significant investment of manpower, so it is simpler (at least for now) to match the existing segmentator to RCX-400 by modifying the optics.

The nominal central obstruction of 12" RCX-400 is 38.4% or 117mm diameter. That leaves the clear segment of pupil $(305 - 117)/2 = 93$mm wide. We can increase the MASS aperture to 85-90mm diameter, and this would result in the improved performance (more flux and better profile restoration). Thus, the preferable pupil magnification would be $90/5.5 = 16.4$, or exit pupil image of 18.6mm in diameter.

In order to get such a magnification with a single Fabry lens, we should select a lens with $f = 100$mm. Such a lens would be located very close to the MASS-DIMM focus, in a space occupied by the viewer flip mirror.

A solution to this problem would be to use a system of two lenses. By selecting the lens parameters, the distance between the lenses x and the distance from the last lens to the focus a, we can change the pupil scale as desired. A possible choice of two off-the-shelf lenses from Edmund Optics (EO) leads to the optical design presented briefly in Table 2 and in Fig. 1. The

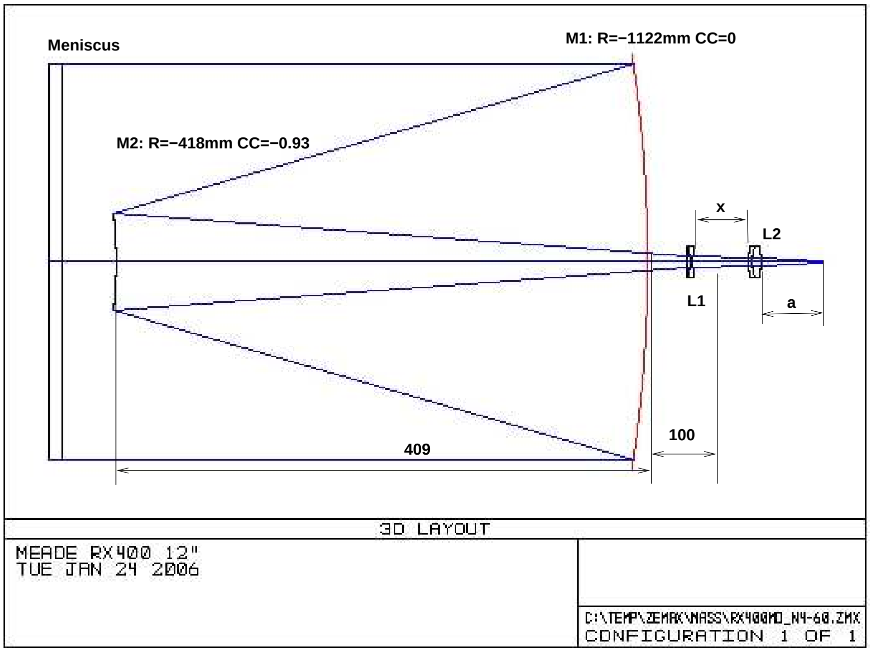

Figure 1: Optical layout of the RCX-400 12" telescope with two lenses.

exit pupil is at 123mm behind the focus and has a diameter 18.7mm (magnification 16.3). It is possible to increase the magnification (get smaller pupil) by decreasing both x and a. The ZEMAX file is rx400_n3c-50.zmx.

Table 2: RCX-400 with a 2-lens coupling to MASS-DIMM

Element	f, mm	Dist. to next, mm	Thick. cent./edge, mm
Meniscus	INF	450	10
Primary mirror M1	-561	411.2	-
Secondary mirror M3	-209.1	511.2	-
Back flange	-	-50	-
Lens L1 EO 45222, $D = 25$mm	-100	$x = 42.0$	4.57/5.81
Lens L2 EO 32325, $D = 25$mm	75	$a = 47.0$	9.50/6.97
Focus	-	-	-

We note that the lens L1 is placed inside the telescope, at about 50mm from the back flange. The telescope was hence "refocused" by increasing the M1-M2 distance. In the first Ritchey-Cretien "proxy" this caused a strong spherical aberration, which could be partially compensated by mounting the lenses L1 and L2 in the inverted positions. However, the Murdock design is much more tolerant to defocus. In fact, by mounting the lenses as shown in Fig. 1 (strong curvature looking to the right, to the focus), we are able to reach high optical quality with the full telescope aperture (Strehl ratio 77%). The image quality in the DIMM sub-apertures is then perfect.

In the initial tests, the lens L1 was mounted with the curved side towards the telescope.

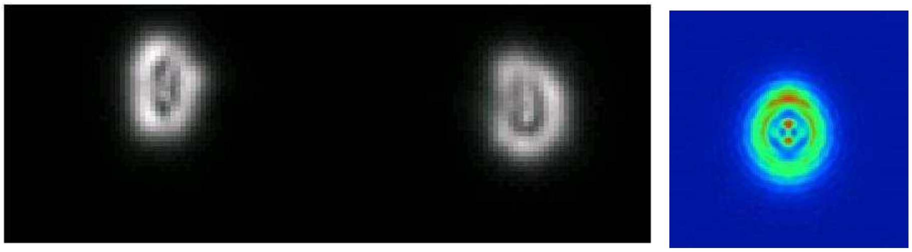

Figure 2: Defocused spots showing astigmatism in the DIMM channel with wrong orientation of L1. Left: tests with the MASS-DIMM, right – Zemax modeling of this effect as an intra-focal image.

In the DIMM images we saw a moderate amount of astigmatism (some 60nm rms as deduced from the image analysis using the donut method) that reduced the Strehls to $\sim 70\%$ (measured Strehls were indeed around 0.6 to 0.7). This effect could be reproduced with the Murdock optical design (Fig. 2). Although even with this aberration the optical quality of the DIMM channel is sufficiently high, we remain confident that by turning the L1 into correct orientation we will achieve near-perfect images. On this occasion, we checked the nominal optical quality of the MASS-DIMM re-imaging channel. Its off-axis spherical mirrors (with the 5.5mm-diameter mask) cause very small astigmatism (12nm rms) which reduces the Strehl by only 1%. By the way, astigmatism is completely irrelevant for operation with the ST-7 detector in the drift scan mode, where the spot images are compressed along one axis.

By tuning the distance x between the lenses and the distance a from the last lens to the focus, we can adjust both the pupil size and the axial position of the pupil image. Actual tests were done with the wrong orientation of L1 and with $a = 47$mm and $x = 39.5$mm. The pupil image was well focused on the MASS-DIMM mask and its diameter was measured as 18.2mm (magnification factor 16.8).

4 Mechanical interface

The new MASS-DIMM units slightly differ from the old ones in their mechanical interface to the telescope. The Fabry lens (or 2-lens adaptor in case of RCX-400) cannot be aligned, but, instead, the whole instrument can be titled with respect to the telescope.

Figure 3 shows the side view of the new MASS-DIMM. It is connected to the telescope by a threaded ring (82.55-mm thread, 3 1/4", 30 TPI). The instrument can be tilted with respect to the ring by means of screws sx1,sx2 (in the x-direction) and sy1,sy2 (in the y-direction). The bottom-left screw s0 has a fixed spacer. The M3 screws sx1,sy1 pull, while the M5 screws sx2,sy2 push. An extra pair of push-pull screws sf1,sf2 can be used to fix the instrument further after the alignment.

Other elements shown in Fig. 3 are the electrical connectors and the PMT shutter (must be closed when off the telescope!). On Fig. 3 (right) the back plate with the segmentator, the DIMM mirrors and the pupil mask are shown. The mask is fixed with 3 M2 screws and can be easily changed to adapt MASS-DIMM to other telescopes. For the RCX-400, the diameter of the DIMM apertures is $d = 5.5$mm and the base is $b = 12.5$mm. With the nominal magnification, this projects to 90mm and 210mm, respectively, at the pupil. The new feature of this MASS-

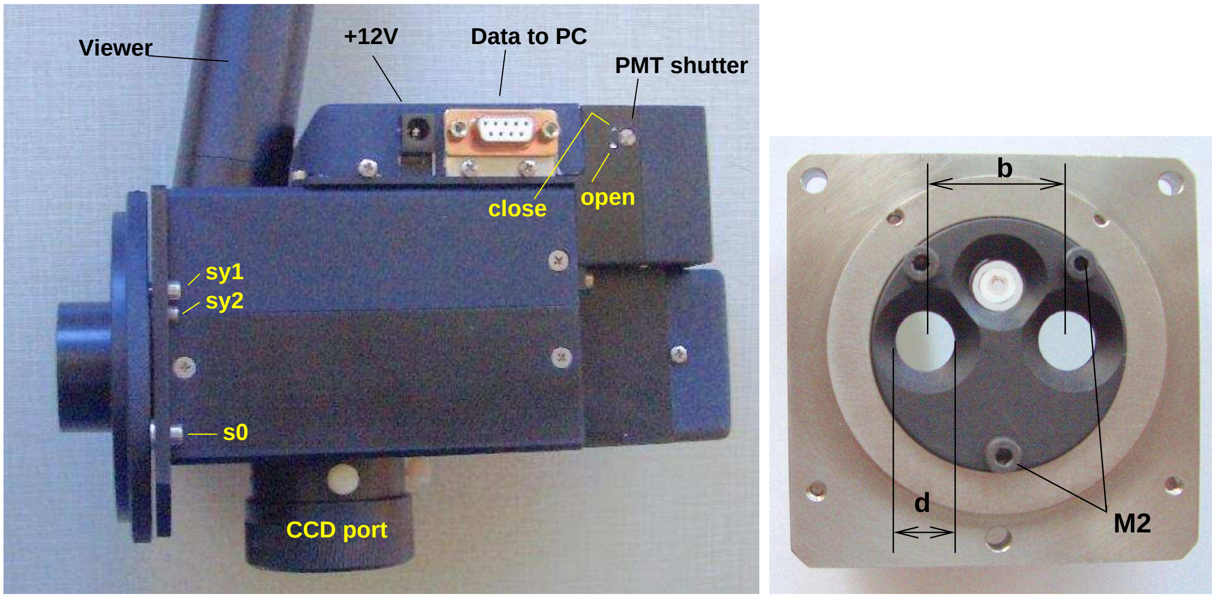

Figure 3: Side view of the MASS-DIMM (left) and its back plate with the pupil mask (right)

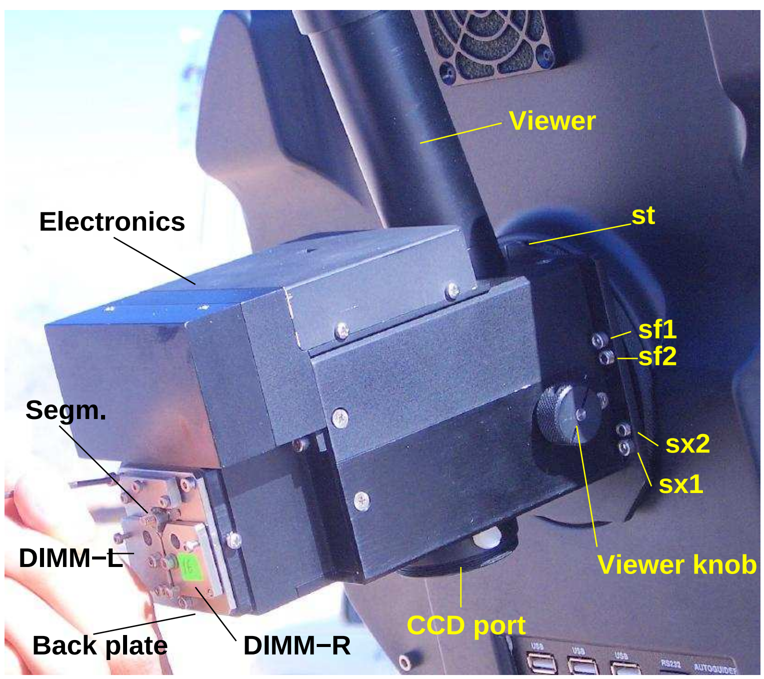

Figure 4: Back end of RX400 with the MASS-DIMM attached.

DIMM is a space around the segmentator permitting to check its alignment by looking from the rear side, without dismounting any elements.

Figure 4 shows the MASS-DIMM instrument attached to the RCX-400 telescope. The orientation is "viewer up" (directed towards the ventilator). After orienting the instrument, tighten the ring with the small screw sf. MASS-DIMM must be mounted on the telescope with the CCD camera already attached. The balance of the telescope with MASS-DIMM should be restored by means of standard counter-weights (no change with respect to Meade LX200).

In order to align the instrument, the back plate has to be temporarily removed, as shown. Be careful not to change the alignment of the segmentator and the DIMM mirrors (DIMM-L and DIMM-R), it is very sensitive and difficult to restore! A plastic mask is placed instead of the back plate and the pupil image is centered carefully with respect to the marks by tilting the whole MASS-DIMM instrument (use the screws sx1,sx2 and sy1,sy2, with sf1,sf2 fully released). This alignment is done during daytime, pointing the telescope to the sky.

When the pupil image is well centered on the plastic mask, the back plate is installed again. By looking at the light passing around the segmentator, make sure that it is not vignetted by the outer pupil edge (from the top) or by the central obstruction (from the bottom). If needed, make very slight adjustments of the sy1,sy2 screws to remove any vignetting. This step is very important for correct MASS operation.

The diameter of the pupil image is practically equal to the distance between the outer edges of the DIMM apertures, 18mm. Any mis-alignment in the x-direction will result in the vignetting of the DIMM apertures. This can be checked by taking defocused images of the DIMM spots (this test also serves for controlling optical aberrations). A slight misalignment in the DIMM channel (up to 10% of the aperture diameter) is acceptable.

Doubled image of the field-of-view can be taken with the CCD, during daytime. If this image is not well centered, the angles of the DIMM-L and DIMM-R mirrors can be slightly adjusted. Be sure to do this adjustment always with tightened central (holding) screws! Apply only very small corrections! This same adjustment changes the relative position of the DIMM spots – their horizontal and vertical spacing.

5 Calibration

As always, the operation of MASS-DIMM depends critically on the hardware-dependent calibration parameters – pupil magnification and pixel scale. The magnification can be determined by measuring the size of the pupil image during the alignment with the transparent plastic mask (see above). Alternatively, a bright light can be directed backwards through the CCD port, and the distance between the inner and outer edges of the DIMM apertures projected out of the telescope can be measured. By comparing it to the physical mask size (Fig. 3), we compute the magnification. The calibration of the remaining MASS parameters is not different from the standard procedure described in the manual.

The pixel size in the DIMM channel is determined by taking images of double stars with known separations (between 20 and 40 arcsec). For example, we measured a pixel scale of $0.85''$ with the ST-5 CCD, corresponding to the equivalent focal length of 1.96m.