1 Instrument setup and preparation

The MASS-DIMM instrument that is installed at the TMT DIMM at Tolar belongs to a series of instruments fabricated jointly at CTIO and Sternberg Institute (Moscow). It is called MD2 (serial number 2). The description of this instrument and its software is provided in separate documents, this document covers only specific installation at Tolar.

1.1 Optical tests

On December 10, 2003, we tested MD2 with ST7 using the simulated star (red laser pointer with optics). Fig. 1 shows the images of the star (with square-root intensity stretch to show the wings) and of the uniformly illuminated field.

It was found that the stellar image focused on CCD is some 1mm above the focal plane of the viewer (as marked by the glass with central hole). This small mismatch was expected from the study of previous MD units, the reason is a slight difference of the focal length of the DIMM re-imaging mirrors with respect to nominal. As the viewer will not be used in regular (robotic) operation, this defect is acceptable.

The images are very sharp, diffraction-limited. They stay well focused when we move the star in the field. The calculation shows that for the wavelength 650 nm (red laser) the diffraction-spot size $\lambda/d = 1.77$ pixels (pixel size 9 $\mu$m, aperture diameter 6.44 mm, distance from aperture to CCD 149 mm). Thus, the image is slightly under-sampled, but should be good for DIMM. The relative position between the spots can be

![Figure 1: Images of the artificial star (left: blow-up, square-root intensity stretch, center: cuts through 3 central lines) and uniform field (right).](image_url)
regulated to within 1 pixel by looking at the CCD images as feedback. It will be difficult to do this without feedback. The stability of the relative image position over time is yet to be determined empirically.

We checked the alignment of the MASS channel. The beams at the re-imaging mirrors are well centered, look uniformly illuminated. The images at the photo-cathodes are centered as well. The optics is clean. The internal blend is not installed (we discovered earlier that it interferes with the DIMM beams).

The Fabry lens of \( F = 140 \) mm is installed. Its holder is of “Meade” (not “CELT”) modification, which explains why its position was slightly different from the expected one at first tests. However, we retain this holder as it was already tested and focused with TMT DIMM in September.

1.2 Electronics check

The electronics of MD2 was tested extensively throughout October-November 2003. In November, some unexpected noise in the signal was discovered and its cause (an error in the microcode) was eliminated. Other MD modules are not yet re-programmed.

We decided not to change the resistor nominals in the electronics module as recommended recently by Kornilov. The reason is that we do not have time for a thorough investigation of the effect of this change, whereas the PMT parameters are adequate without the change. The text below lists main PMT parameters as found in our tests.

<table>
<thead>
<tr>
<th>Device 2</th>
<th>HV=800</th>
<th>LED=0.1</th>
<th>t=+23°C</th>
<th>10-Dec-2003</th>
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<td>Thresh</td>
<td>Flux</td>
<td>P</td>
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<td>S+</td>
<td>0.3</td>
<td>194</td>
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<td>B</td>
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<td>M</td>
<td>0.4</td>
<td>1140</td>
</tr>
<tr>
<td>C</td>
<td>AJ4149</td>
<td>L</td>
<td>0.5</td>
<td>1519</td>
</tr>
<tr>
<td>D</td>
<td>AJ4560</td>
<td>S++</td>
<td>0.4</td>
<td>217</td>
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</table>

A somewhat elevated PMT noise in the D channel (non-poisson parameter 1.13) is related to the individual properties of this particular PMT (very short plateau region, S++). This is of no consequence to operation (the flux in D is highest). However, we checked that even at very low flux the scintillation indices in all channels are measured correctly. This was done by means of the “Statistics test” in the Turbina software. The match of expected and measured scintillation indices is within 0.0001, even for a flux of 14 pulses per millisecond per channel, which means that the photon noise is subtracted correctly. The same match extends to high fluxes, indicating that the non-linearity parameter was determined well.

2 Installation

MD2 has been attached to the telescope on Dec. 13, 2003 (Fig. 2).

Cabling. The MASS signal cable (RS-485 interface, two D-connectors) and the power cable (+12V extension), both 12m long, were passed through the central hole in the azimuth axis, where other cables go as well. This was done by passing a thick wire first, then attaching both cables (with D-connector shell removed) to this wire with scotch tape, and pulling the cables up by the wire. The cables go through the hole (specially made) in the fork cover, as seen in the Fig. 2, then they are brought up the fork, joined with the CCD cables (that go out of the hole in the fork) and make a loop before connecting to the instrument.
The MASS power supply is plugged into the remotely controllable 110V outlet number 2 in the electronics cabinet. Thus, MASS can be powered under computer control. The MASS signal cable is connected to the LPT port of the laptop PC through its converter.

**Instrument installation.** The ST-7 camera (serial number 03043307XME) is attached to MD2: its threaded ring is removed by loosening 3 screws, the ring is threaded onto MD2, then ST7 is put back on the ring and fixed at correct position angle by its screws (Fig. 2). Be careful to tighten the ring (with CCD on), then to re-adjust the angle.

The 140-mm Fabry lens in its holder (Meade modification) is put inside the front tube of MD2. The upper end of the lens holder is 2mm deep inside the tube. The rotation is fixed by the plastic screw.

The MD2 with CCD is bolted to the telescope, so that the viewer looks at 45° with respect to the alt axis of the telescope. The viewer is removed and its angle is tapped with the plastic cover.

**Alignment.** First, we removed the MD4 steel plate (with DIMM and MASS mirrors) and installed the transparent alignment plate where the approximate locations of the apertures are marked. The pupil is well focused on this plate, we centered it by moving the Fabry lens with 1.5mm Allen key. The outer edge of the pupil coincides with the outer edges of DIMM apertures. Comparing the size of those features, we find the optical magnification of $\frac{350}{21.3} = 16.4$ (revised below to 15.5). The MASS aperture is conveniently placed in the center of the free aperture segment with some margin, hence its alignment is not critical.

It was found that the real DIMM apertures (as opposed to the marks on alignment plate) are not perfectly centered: the defocused images of a star on the CCD show that one spot is vignetted from the outside. On Dec. 14, the CCD and MASS electronics were removed during daytime and the DIMM apertures were fine-centered by looking into the CCD beam and moving the Fabry lens. The vignetting is made symmetrical, is really small (less than 5mm of each aperture are chopped off by the outer edge of the pupil). Thus, DIMM baseline is $15.5 \times 16.26 - 2mm = 250$mm, DIMM aperture diameters are $15.5 \times 6.44 = 100$mm.

At the same occasion we verified that the image of MASS D-aperture (as seen at the place where PMT should be) is not obstructed by anything.

It should be noted that there is no shutter in MASS. Hence, the PMTs are not protected from the daylight. It is critical to turn off the high voltage at the end of the night.
3 Calibration

MASS calibration consists of measuring the magnification between the segmentator and entrance pupil. It was not done in back-illumination (as usual), but rather by noting that the outer edges of DIMM apertures touch the pupil border. We assume the pupil to be 350mm in diameter. If the distance between the outer edges of DIMM apertures is 22.7mm (nominal), and the pupil size is 22.5mm (we estimate vignetting as 2*0.1mm), the magnification is 350/22.5=15.55. As noted above the initially adopted value is 16.4. Previous direct measurement of the magnification at TMT DIMM (September 29, 2003, with a different mask but otherwise same optics) gave 15.5. The nominal magnification as calculated from the optical parameters of the telescope and MASS-DIMM optics is 15.52.

DIMM calibration consists in measuring the pixel scale. The MD2 was pointed to a double star HR 8895 (separation 26.46\"). The measurement of the distance between the two images gave a pixel scale of 0.78\" (Matthias: TBC, what is the accuracy?). This is very close to the estimated value. Indeed, MD2 reproduces the telescope focal plane with a magnification of 0.876; combined with the telescope nominal focal length of 2800mm and the pixel size of 9 \(\mu\)m, this leads to 0.756\" “theoretical” pixel scale.

The best focusing corresponds to the spot separation of 31 pixels. It remains to be seen how stable this separation is as a function of temperature, time, etc.

4 Integration of the software

Most of the problems in the MD2 installation were related to the implementation of its operation in the robotic system. This was expected: the creation and debugging of robotic DIMM took several months, an addition of a new component could take at least several days.

The MASS software, Turbina, and the RS485 driver were installed and tested on the laptop without problems. Turbina was configured to communicate with the Supervisor (SV) on port 16007 (6007 on the first night). The communication was tested beforehand (from California), the connection to the instrument was also tested before going to Tolar.

Turbina has as yet several bugs and does not communicate with the SV as it should. The other problem is the interactive nature of Turbina that complicates the robotic operation. Any problem (e.g. loss of connection with the instrument) results in a pop-up dialog window and hangs the Turbina execution in wait of user reaction. There is no one to react interactively, so the interactivity (or its remnants) must be neutralized.

The solution adopted by Matthias consists in launching the Turbina from the SV and killing it when the operation is ended or something unexpected occurs. The command Park should be issued first to switch off the high voltage on the PMTs. Additionally, MASS is unpowered at the end of the night. If everything fails, the system of over-light protection of PMTs turns off the HV as well, but this is indeed the last protection before burning the instrument.

It was important to program the robotic control so that it would react adequately to any unexpected behavior of Turbina, assuring the normal operation and shutdown of the TMT DIMM. This did not happen the first night: the SV crashed and the telescope remained open with the instrument powered. Fortunately, the PMTs were protected by the overlight feature of MASS electronics. An additional temporary protection (cut of power and dome closure in the morning independently of the SV) is installed by Matthias on Dec. 14.
5 Control of the MASS data quality

First nights of the MASS operation at Tolar have shown that the quality of the profile restoration is not high. The normalized residuals of model fitting (fixed layers) are in the range 100 to 500, whereas the normal values should be around 10. The reason is a systematic deviation between the indices and the model (Fig. 3). This behavior was not observed on two other MASS-DIMM units recently tested at Cerro Tololo and La Silla.

Our first attempt to improve the situation was made on December 16 by changing the (wrong) calibration coefficient $k = 16.4$ to a better value $k = 15.5$ (see above). The weighting functions were re-calculated. However, as seen in Fig. 3, the systematics of the residuals was not improved. On all nights, the index in the channel B has always large negative residuals, in all other channels the residuals are smaller and positive. The residuals of the differential indices involving B-channel (AB, BC, BD) are also mostly negative.

The flux ratios in all channels are stable during the night (and from night to night) to better than 1%. This excludes any possibility of photometric errors caused by the dust, optical defects, etc. The scintillation indices measured on simulated light were good in all channels, thus the electronics and software work well.

By examining an identical instrument (MD5), we found that a possible source of photometric errors could be related to unwanted reflections (ghosts) within the instrument. There are two ways by which some extra light penetrates into the MASS channels:

1. Part of the light falling on CCD is reflected back, reaches the segmentator and then is focused on the PMTs by the re-imaging mirrors. In Fig. 4 the picture of this ghost is presented. A bright aluminum foil was placed instead of the CCD to accentuate this effect, while the telescope beam was simulated by a red diode laser with suitable optics.

2. The mask that defines the DIMM and MASS apertures is not quite black and has some specular
reflection. The light falling on the mask just outside the segmentator is reflected toward the re-imaging mirrors and reaches PMTs in channels B and C. This only happens if there is some margin between MASS apertures and outer edge of the pupil (which is the case for TMT). By the way, the same happens in the DIMM channel, but this small unfocused light is negligible compared to the intensity of the spots.

In order to quantify the ghosts, measurements were done on December 18, 2003. The flux of the laser source was measured by the MASS channels with the ST7 placed and removed repeatedly. The sensitivity of PMTs to red laser light is quite low, permitting to use bright source. The background was also measured (with laser off) and found negligible (less than 0.1%). The difference in flux with and without CCD (or aluminum foil) was barely noticeable (masked by some variation of the source intensity), a firm upper limit on the intensity of the ghost is 1.3% in all channels. The segmentator participates in the formation of this ghost, hence the relative intensity of the ghost is roughly the same in all channels.

The flux of the laser was measured with and without the segmentator. This permits to estimate the flux reflected by the mask (and, potentially, by other optical elements). Again, the background was found negligible. The intensity of the scattered light was found to be 1.7%, 0.75%, 0.28%, and 0.36% in A, B, C, and D, respectively.

It is relatively easy to eliminate the ghosts. A simple mask can be installed in the MASS light path to cut the light reflected from the CCD (ghost 1). To eliminate ghost 2, the aperture mask can be covered with a black paint and/or tilted.

The effect of ghosts is thus quite small. Scattered light of 2% will reduce the scintillation index by 4%, whereas we find that in the B-channel the index is reduced by at least 15%. Thus, the problem remains unsolved.