Testing the restoration in MASS-DIMM

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1 Motivation

The MASS-DIMM instruments being developed now at Sternberg/CTIO will work with smaller apertures than the first MASS. This choice is made partially as a result of optimization studies that have shown the profile restoration quality to benefit from somewhat smaller apertures, and partially for practical reason: the width of the unobstructed pupil ring on Meade 10-inch telescopes is only 80mm. The approximate diameters of MASS ring apertures for Meade and for the CELT telescopes are listed below (in cm):

Segment	Meade	CELT
A	1.9	2.0
B	3.15	3.35
C	5.6	6.0
D	8.0	8.5

The purpose of this report is to check the restoration quality for the actual aperture diameters. This depends on the weighting functions, which were computed for a central wavelength 450 nm, FWHM band-pass 100 nm and "quasi-Gaussian" spectral response. This is a reasonable approximation to the real MASS passband as defined by the filter, photocathode, and stellar spectrum.

Another approximation in this study is an assumption of independent errors on all scintillation indices. The level of errors (2% relative on all indices, except 4% on AB) corresponds to the real estimates of those errors which likely include a significant contribution due to turbulence variation (non-stationarity) during for 1-min. integrations used in MASS. Hence, I may actually over-estimate the errors of profile restoration in this study.

2 Least-squares analysis

Two methods were used. **First**, I tried the IDL program massopt2.pro that solves the least-squares (LS) problem of profile restoration and computes the formal errors. The inverse condition number of the LS normal matrix tells how good a given set of weighting functions is for disentangling the pre-defined layers. The quality of restoration is assessed by the largest formal error of the restored intensity relative to the total profile integral (it was shown that MASS keeps constant the relative, not absolute error as turbulence intensity changes). The LS restoration method is linear, not taking into account profile non-negativity. This additional information is used in the actual restoration. Attempts to use the standard altitude grid with 6 layers at 0.5, 1, 2, 4, 8, 16 km fail, giving huge errors. In the following I use only five layers, excluding the 0.5 km layer.

Compared to the previous study of MASS restoration (MNRAS paper, 2003), I checked also the case when MASS is looking at 45° zenith distance. We keep the fixed layer altitudes, so the altitude grid is expanded $\sqrt{2}$ times. The Fresnel radius is proportional to the square root of propagation distance, so one would expect that the optimum aperture diameters for 45° zenith distance will be $2^{1/4} = 1.19$ times larger.

In the Table below I list the aperture diameters D,C,B,A in cm, the zenith distance, the inverse condition number of the LS normal matrix multiplied by 10^5, and the maximum relative error r which is found at the lowest layers. The results (r) depend on the input profile, but only slightly; I used mostly the model with 0.6 energy fraction at 1 km and 0.2 fractions at 4 and 16 km, but checked other plausible profiles as well.

[DCBA] diam., cm	z, deg.	Cond^{-1} $\times 10^5$	$r_{\max}$
8.0, 5.6, 3.15, 1.9	0	14	0.10
8.0, 5.6, 3.15, 1.9	45	3	0.17
8.5, 6.0, 3.35, 2.0	0	14	0.08
8.5, 6.0, 3.35, 2.0	45	8	0.11
8.0, 7.0, 3.1, 1.9	0	12	0.09
8.0, 7.0, 3.1, 1.9	45	10	0.09
8.0, 5.6, 4.0, 2.8	0	11	0.11
8.0, 5.6, 4.0, 2.8	45	7	0.14

The conclusions from this Table are that the chosen apertures are indeed near-optimum because the condition number and error are relatively insensitive to exact aperture diameters and to the zenith distance. A slight reason for worry is the case of Meade at 45° zenith distance. Somewhat better distributions of segment diameters can be suggested for the outer diameter of 8 cm (4 lower lines). The last option is an exact $\sqrt{2}$ ratio of aperture diameters.

The "optimization" of apertures is carried out with respect to the selected altitude grid. We may work the other way and adjust the restoration grid to the available apertures. Attempts to change one or two altitudes of the "standard" logarithmic grid were not successful. When I scale the whole grid with some factor, the evolution of the condition number vs. this factor can be traced, to see the optimum range for a given aperture selection. Thus, the last option ($\sqrt{2}$ diameter ratio) gives equal performance for z-grid scaling of 1 and 1.2, corresponding to zenith distances from 0 to 33°. The standard Meade solution is indeed optimized for zenith and its performance degrades slightly on both sides of the optimum (scaling factors more and less than 1). Thus, if we select the restoration grid with a factor 0.8, its performance will be optimum at moderate zenith distances and will be slightly worse at the extremes of the MASS zenith range – 0 and 45°.

3 Moving layers

The **second** analysis method simulates the actual restoration procedure (non-negative layer intensities) for one or two layers with variable altitudes ("moving layers"): massxx.pro for 1 layer and massx3.pro for 2 layers. The 5-layer altitude grid starting at 1 km is implemented. I simulated the case of 45° zenith distance as well.

The 1-layer restoration with nominal Meade apertures (Fig. 1) is near-perfect, as expected. A "glitch" at 9.8 km seen in the Figure is a failed minimization; curiously, it repeats in different runs of

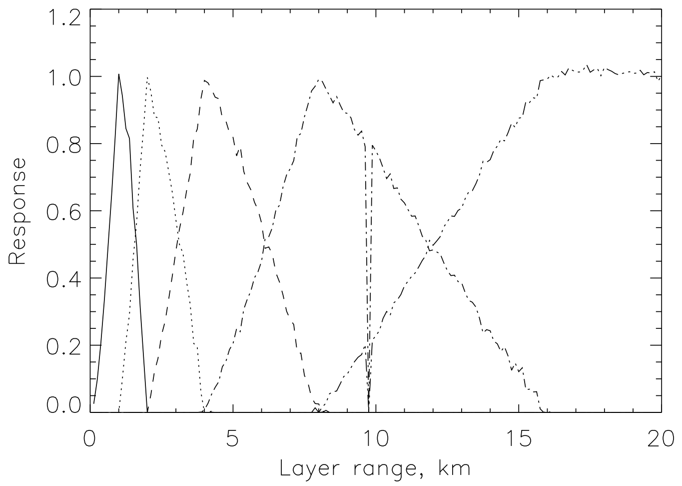

Figure 1: Restoration of one layer with variable altitude (horizontal axis) with nominal Meade apertures.

the code.

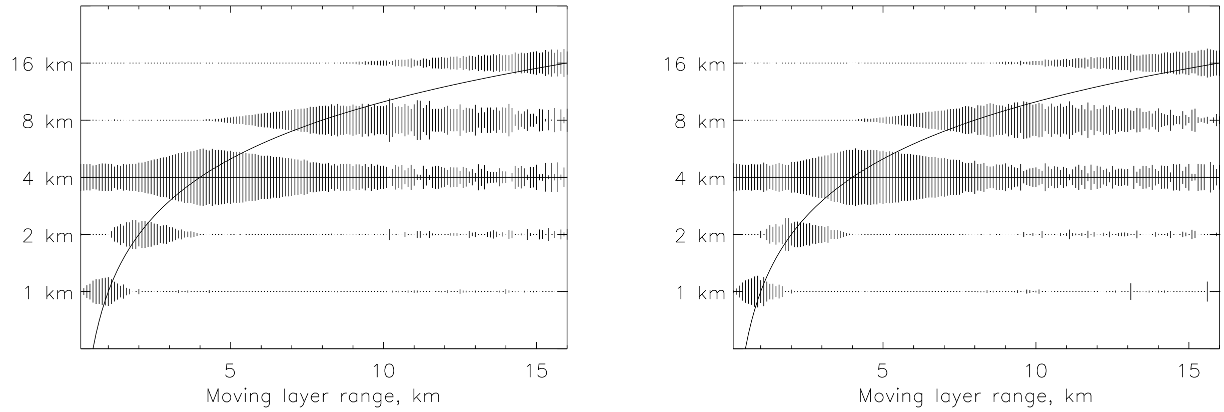

Figure 2: Restoration of two equal layers (one fixed at 4 km, the other moving) with nominal Meade apertures (left) and with modified apertures of [8,7,3.1,1.9] cm diameter (right).

In Fig. 2 the two-layer case results are shown. This is the most critical test of the restoration code demonstrating its ability to split the layers. The increased "noise" is mostly related to a re-distribution of the energy between the layers, the "noise" on the total restored intensity is still less than 10%. It is seen that the re-distribution of MASS aperture diameters suggested by the LS analysis does not lead to any noticeable improvement of the restoration quality.

In Fig. 3 a more critical test for viewing at 45° zenith distance is shown. Again, I do not see any noticeable improvement in going from nominal to modified apertures. In this Figure, the horizontal axis is extended to 20 km to show how the system reacts to a layer that is above the highest modeled altitude. In attempting to represent the scintillation indices with the (inadequate) model, the restoration procedure "pushes" the 4-km layer at a lower altitude, and thus some energy in the 2-km layer appears. The same behavior was observed with the old (large) MASS apertures. The measurement of

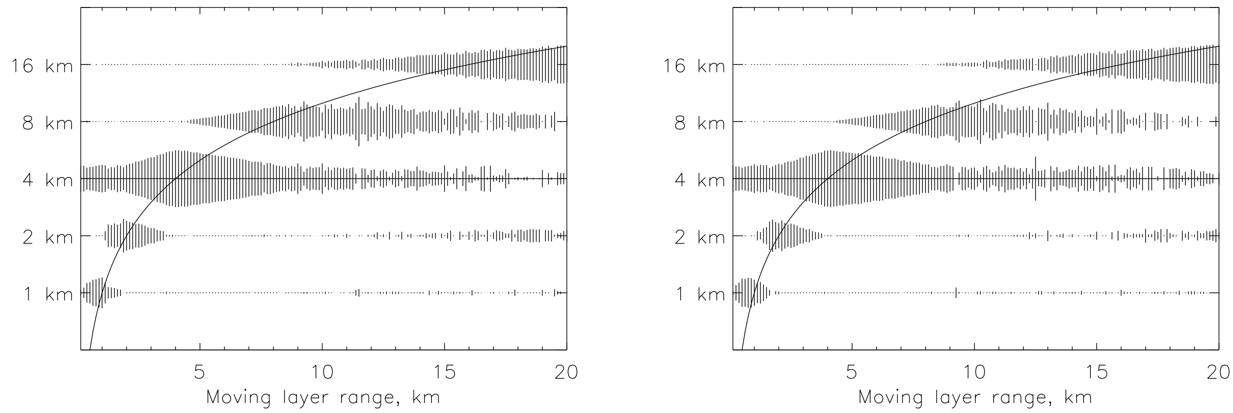

Figure 3: Restoration of two equal layers (one fixed at 4 km, the other moving) with nominal Meade apertures (left) and with modified apertures (right) for the 45° zenith distance.

the total turbulence integral remains excellent.

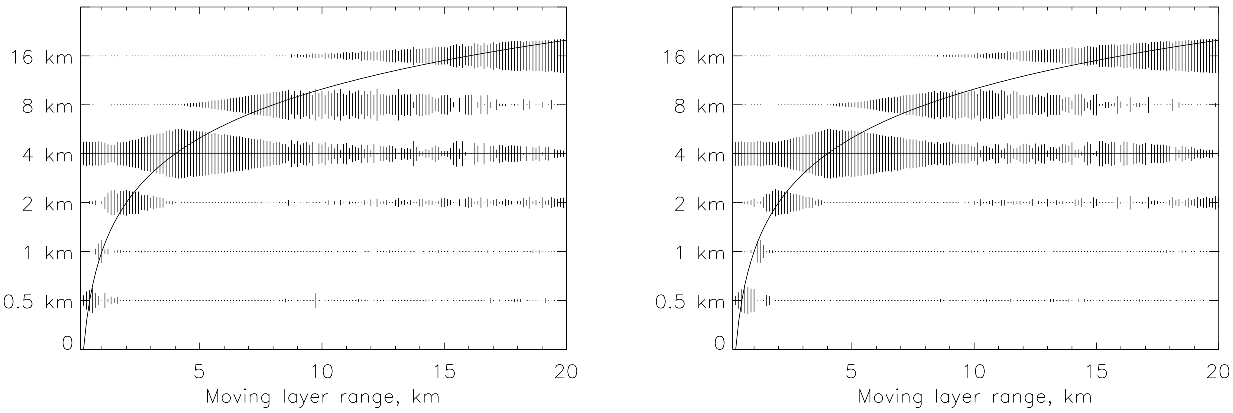

Figure 4: Restoration of two equal layers (one fixed at 4 km, the other moving) with nominal Meade apertures (left) and with modified apertures (right) for the star at zenith and 6 model layers.

Figure 4 displays a case of 6-layer model for viewing at zenith. The discrimination between 1 km and 0.5 km layers is noisy, as expected. I recommend to restrict the fixed-layer model to 5 layers. In case of significant turbulence below 1 km, the floating-layer model will retrieve the correct altitude. For 6-layer restoration the plot of the total intensity versus altitude shows a characteristic "hump" at 1 km (see MNRAS paper), whereas for 5-layer model it is constant down to 1 km and then starts to decline.

4 Conclusion

The study shows that the exact choice of the segmentator diameters is not critical: some deviations from the optimum choice are permitted. The current Meade nominal diameters are indeed optimum (highest restoration quality) for the selected logarithmic altitude grid, with some degradation of performance away from zenith. The need to work at non-zero zenith distances was over-looked in the choice of MASS apertures. This over-sight can be easily corrected in the software by a slight modification of the altitudes, so that the optimum logarithmic distances (for which the segmentator was designed) will be reached at some non-zero zenith distance. Even without this modification the profile restoration quality remains good.