Experiments with MASS

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1 The purpose and circumstances of the experiment

As more experience is gained with operating MASS turbulence profiler, the method itself deserves more through study. One troubling issue are the "over-shoots" where MASS shows a larger integrated seeing than DIMM. It has been noted that overshoots are related to the conditions of bad seeing, namely strong scintillation and fast turbulence. Is it possible that data processing in MASS is somehow flawed under those conditions? The purpose of the experiments described below is to clarify this issue.

A priori, one would expect that under strong scintillations the MASS signal would saturate and the measured seeing would be under-estimated. Direct numerical simulations confirm this statement, making "overshoots" even more puzzling. Similarly, when the turbulence is fast, the 1ms exposure time of MASS could be insufficient to "freeze" the signal. A correction to zero-exposure is made in the data processing, but the actual efficiency of this correction remains to be proven.

On the night of October 7/8 2004 AT and VK conducted experiments with the MASS device working in the Cerro Tololo seeing tower. The night had bad and fast seeing as required for this study. The evening of October 7 was cloudy. The sky cleared up shortly after sunset, but the humidity remained very high (near 80%). We had to remove the mist from the corrector lens of the Meade telescope 3 times during the experiments by heating it with a warm fan. The humidity dropped sharply after 6h UT.

During these experiments, two similar MASS instruments also worked at the TMT site-testing telescopes located few meters from the seeing tower. These are called T2 and T3, the data from T3 are taken for comparison here.

VK re-programmed the acquisition module of MASS for 2 Mbaud exchange rate (the nominal rate is 460 Kbaud), enabling the acquisition of photon counts with a 4-times shorter exposure, 0.25 ms. The exposure time was controlled form the MASS software and could be set to its nominal value of 1 ms. The flag that enables saving individual photon counts was set in the Turbina program, and these data were analyzed subsequently in great detail. After finishing the experiment, the seeing monitor and MASS were returned to their nominal configuration and worked in the standard regime. However, saving of the photon counts was still enabled. These data were also used in the analysis presented below. For clarity, only part of the nightly data is displayed in the plots.

In order to test the saturated scintillation regime, we pointed the telescope to a low star, α Car. After taking some data, we returned to a star near zenith, then re-pointed to α Car again. The schematic of our experiment is shown in Fig 1. superimposed on the turbulence profiles restored from these data. It can be seen from Fig. 2 that the "overshoot" was more or less permanent during these experiments, becoming very strong between 6h and 7h UT, when the seeing was poor. The scintillation was strong, the index in the smallest A-aperture even exceeded one (Fig. 3).

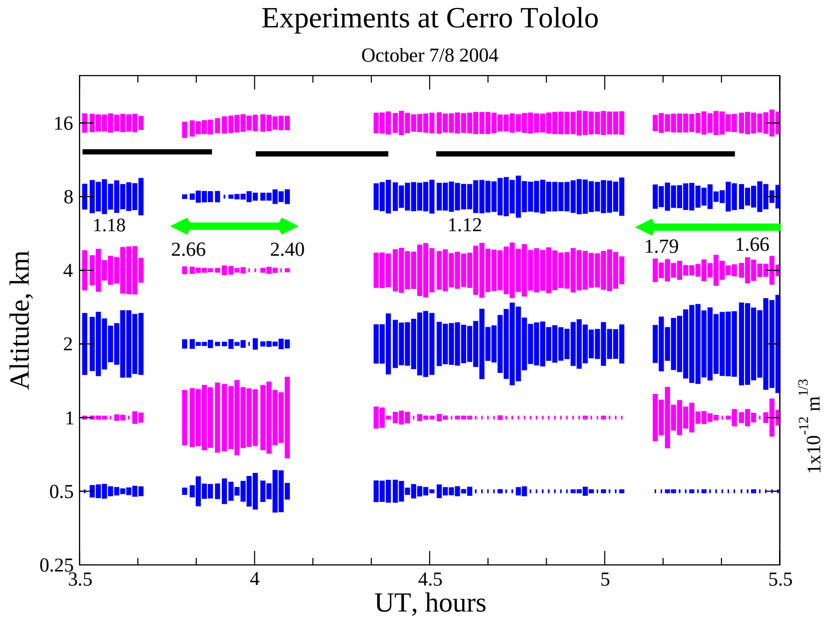

Figure 1: Scheme of the experiment and the turbulence profile. The green arrows indicate periods when a low star was observed, the numbers showing the air mass. The periods of data acquisition with 0.25 ms exposure are marked by horizontal black lines.

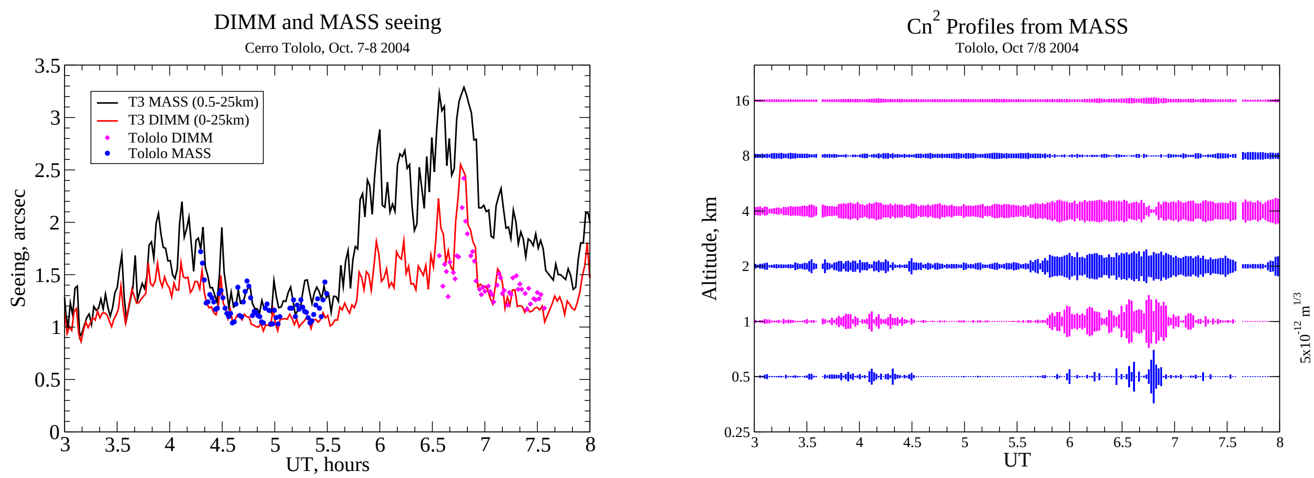

Figure 2: **Left:** Seeing as measured with T3 MASS-DIMM and with the Tololo monitor. **Right:** Turbulence profile as measured by the T3 MASS-DIMM.

2 Distribution of photon counts and index calculation

The results below refer to two 1-min. segments starting at 03:30:23 and 06:33:44 UT, with 0.25 and 1 ms time resolution, respectively. VK processed count data and computed second moments. The results turned out to be identical to those computed by Turbina. Thus, we verified that moment-calculation routine works correctly under strong scintillation regime.

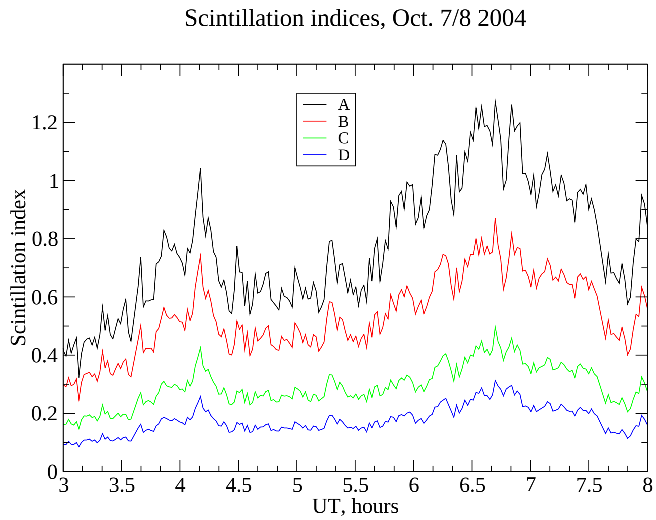

Figure 3: Scintillation index as measured by the T3 MASS-DIMM.

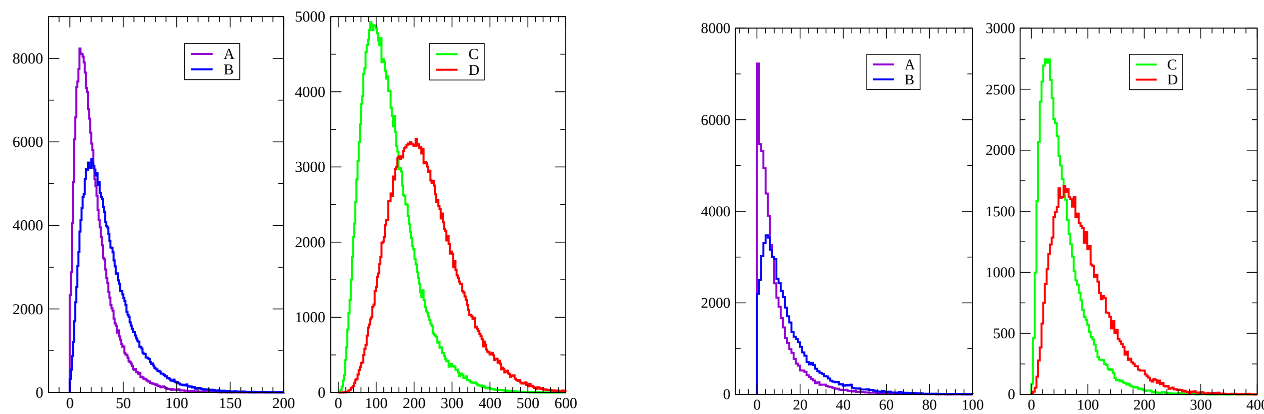

Figure 4: The distributions of individual photon counts in MASS channels A,B,C,D for two data segments registered with 0.25 ms resolution (UT 03:30:23, left; scintillation indices 0.57, 0.44, 0.26, 0.16) and 1 ms resolution (UT 06:33:44, right, scintillation indices 1.44, 0.96, 0.56, 0.36).

The distributions of individual counts in four MASS channels are shown in Fig. 4. When the scintillation index is small (left, D-aperture), the distribution is close to normal (Gaussian). Under strong scintillation (right) the distribution is log-normal, with a very long tail. However, it is not strictly log-normal either because the scintillation signal is combined with the Poisson distribution of photon counts. This effect is most spectacular in the A aperture, where the most frequent number of detected photons is zero.

The calculation of indices under strong scintillation depends on the formula used. In the MASS software, Turbina, we use the linear formula because it permits easy and correct subtraction of the photon-noise variance. The logarithmic formula gives smaller indices. It turns out that in the regime of saturated scintillation the linear formula saturates less than the log-formula. Thus, the use of the linear formula is doubly justified.

3 Temporal variation

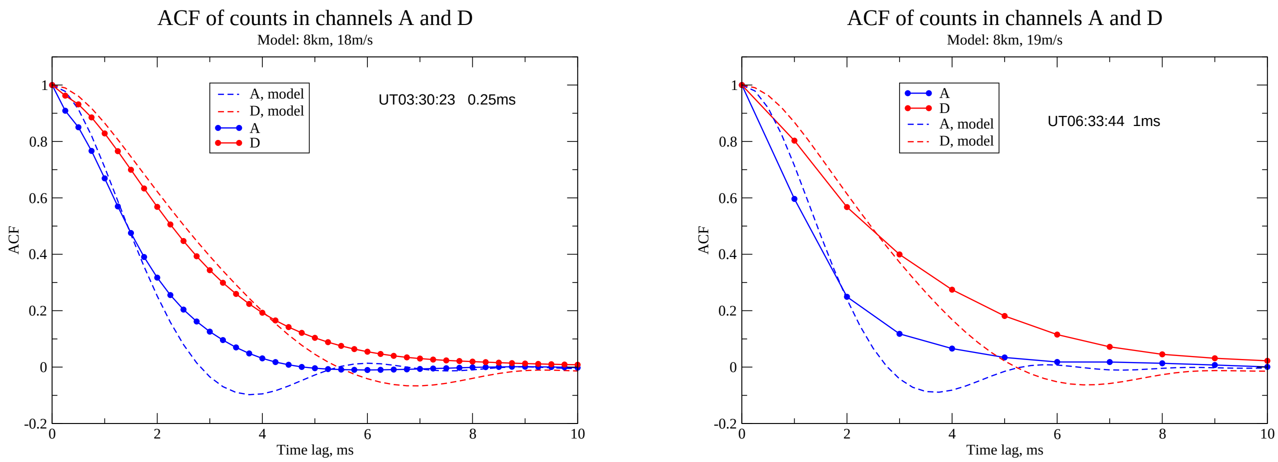

Figure 5: Auto-correlation functions of the photon counts in channels A and D computed from the data with 0.25 ms (left) and 1 ms (right) resolution. The one-layer models are plotted in dashed lines.

The autocorrelation functions (ACFs) of photon counts were computed by VK from 1-min. segments of data (Fig. 5). They are compared to the theoretical ACFs that correspond to a single turbulent layer moving with constant velocity. The IDL program `tempsp.pro` computes the 2-dimensional power spectrum of scintillations filtered by a MASS aperture, integrates it on one axis and re-scales with the wind velocity to obtain the temporal spectrum and the ACF. The averaging of intensity during MASS micro-exposure is taken into account as well. The parameters of the model (altitude and wind velocity) were adjusted roughly to match the width of the experimental ACFs. It can be seen that the fit is poor, presumably because the actual temporal behavior of the signal results from a combination of layers with different altitudes and velocities. The altitude of the modeled layer had to be set to 8 km, otherwise the model ACFs for the circular D-aperture display a characteristic "kink" not seen in the data. The dominating layer, according to T3 MASS, was close to 4 km, but the D-aperture is mostly sensitive to higher layers, explaining this apparent contradiction. On the other hand, the derived wind velocity is consistent between two data sets and matches expected values from the atmospheric model [TBC].

The same 1-layer model permits to calculate the bias introduced into scintillation indices by the "zero-exposure" correction. The correction consists in adding to the 1-ms indices the difference between 2-ms and 1-ms indices, i.e. linearly extrapolating the dependence of the variance on exposure time to zero. This correction is actually computed as $s_0 = 1.5 s_1 - 0.5 \rho_1$, where s_1 is the 1-ms variance and ρ_1 is the covariance with time lag 1 ms. The model predicts that the correlation ρ_1 / s_1 is about 0.7. Indeed, this corresponds to the observed correlation (Fig. 6, left) which was stable during our experiments.

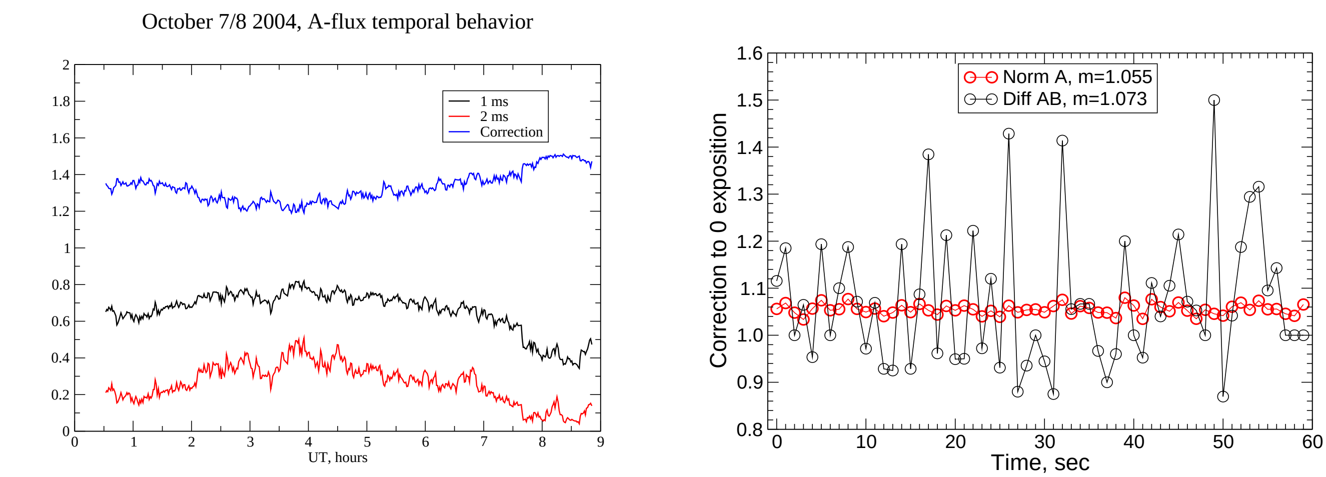

Figure 6: **Left:** The correlation coefficient of A-aperture scintillation with time lag 1ms (black) and 2ms (red), and the amplitude of the correction to zero exposure time (blue). Data from T3 MASS-DIMM. **Right:** Over-correction of the normal (A) and differential (AB) index determined from the 0.25-ms data (UT 03:30:23).

The 1-layer model shows that linear extrapolation to zero should over-estimate the A index by 6%. Indeed, if the true value of the index is computed from 0.25-ms data, we find that on the average we over-estimate the index by 5.5% (Fig. 6, right). The differential index is also over-estimated by some 7%. Such a small bias incurred in the conditions of fast turbulence is reassuring. In the future, we can implement a mild correction $s_0 = 1.25 s_1 - 0.25 \rho_1$ that, according to the model, is better. However, both actual and mild corrections would "undershoot" if the wind were faster.

It is evident from Fig. 1 that switching the exposure time from 1 ms to 0.25 ms and back had only minor effect on the restored turbulence profiles. Thus, we may be confident that even under fast turbulence conditions the correction for finite exposure works reasonably well.

4 Discussion of MASS biases

We have shown that in conditions of strong and fast scintillation the indices in MASS are computed correctly, with a tiny over-estimation of few percent owing to zero-exposure extrapolation. Where does the over-shoots come from?

Looking at Fig. 1, we see that the turbulence profile (TP) reconstructed on the low-altitude star is wrong. All normal scintillation indices heavily saturate and are under-estimated. The differential indices, however, do not saturate (this has been born out by our simulations). Thus, the restoration procedure of MASS gets wrong input signals and, consequently, fits the wrong model that "places" most turbulence at low altitudes. As the air mass decreases, the error in profile restoration becomes smaller. MASS works with air mass less than 1.5, hence no such effects are expected in normal operation. Curiously, the seeing measured by MASS on a low star was only slightly smaller than the seeing measured by the T3 MASS. Seeing is mostly estimated from the differential index AB that does not suffer from saturation. We note also that wrong profile restorarion did not show in the increased residuals: the set of scintillation indices could be adequately represented by the 6-layer model. Thus, wrong restoration does not always show up in the residuals.

When scintillation saturates even at zenith, a similar behavior is expected. The restoration procedure would try to model the data by turbulent layers at altitudes that are lower than in the actual atmosphere. We need to do more modeling to access the importance of this effect and its consequences. If this hypothesis is true, the "packet" of turbulence seen by the T3 MASS between 6h and 7h UT would be located much higher than 1km shown in Fig. 2.

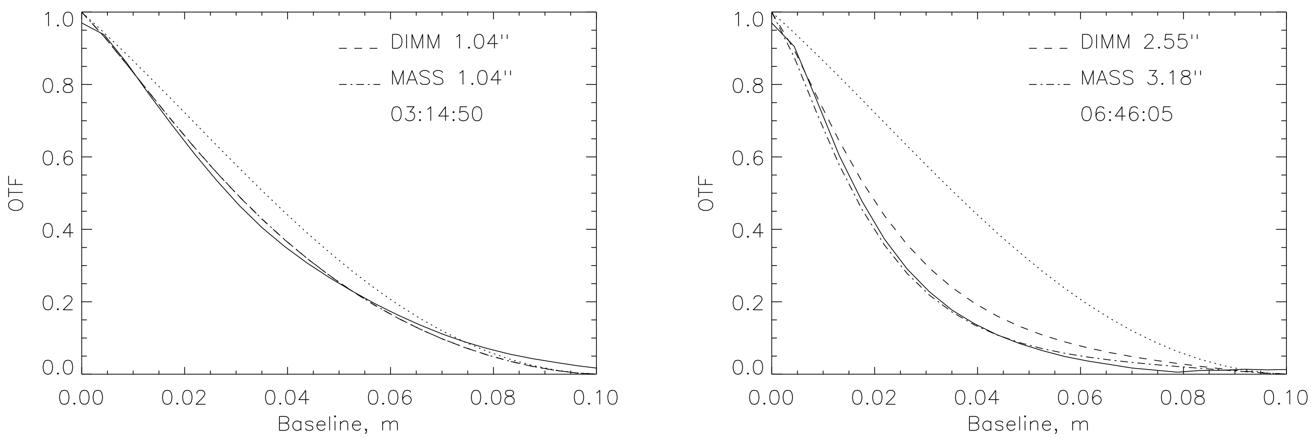

Figure 7: The width of spots in T3 DIMM is evaluated by comparing the experimental OTFs (full lines) with the short-exposure models resulting from the seeing measured by MASS and DIMM (dash-dot and dash, respectively). The diffraction-limited OTF is plotted in dotted line.

Which instrument measures the correct seeing during "overshoots", MASS or DIMM? The answer is not found yet. In Fig. 7 we compare the width of the spots in T3 DIMM with the expectations from a short-exposure atmospheric PSF (the details are given in separate report). When MASS and DIMM were in agreement, the spots were adequately described by the model. During very bad seeing, the spots rather match the seeing given by MASS...

We plan to investigate further the issue of overshoots by complete Monte-Carlo simulation of both MASS and DIMM under strong scintillation. The temporal effects will be included as well.