MASS overshoots: a case study

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1 The problem of overshoots

A new method of turbulence measurements based on single-star scintillation has been introduced in 2002 when Multi-Aperture Scintillation Sensor (MASS) became operational. MASS measures turbulence integral in the atmosphere starting from ∼500m above ground. From this integral, a seeing in the "free atmosphere" is deduced.

The Differential Image Motion Monitor (DIMM) measures the turbulence integral (hence seeing) in the whole atmosphere. The "DIMM seeing" must always be less or equal to the "MASS seeing". Extensive experience gained with simultaneous operation of MASS and DIMM at various sites has shown that this is indeed the case almost all the time. However, during the periods of bad seeing MASS sometimes measures more than DIMM. This phenomenon has been called "overshoots" of MASS.

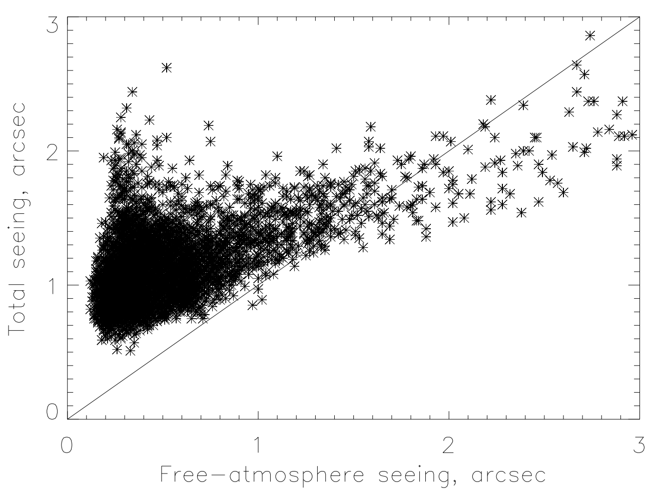

Figure 1: Seeing measured by MASS and DIMM at Cerro Pachón in January 2003.

The phenomenon of "overshoots" is illustrated in Fig. 1 with the data obtained during 21 nights at Cerro Pachón. Clearly, overshoots never happen when the seeing is better than $1''$. However, overshoots do cast some doubt on the validity of MASS and DIMM data and on the possibility of estimating the turbulence in the ground layer by subtracting turbulence integrals measured by DIMM and MASS.

The principles of DIMM and MASS are very different. MASS is based on scintillations (amplitude fluctuations), while DIMM uses wave-front tilts (phase fluctuations). The spatial scale of optical disturbances sensed by those instruments is also different, being 2-10 cm for MASS and 10-20 cm for DIMM. So, the good general agreement between MASS and DIMM manifests the validity of the underlying theory – Kolmogorov turbulence spectrum and weak-perturbation (Rytov) approximation.

In this note we analyze one specific data set showing overshoots, in hope to find out the reason of this phenomenon. The data have been obtained on the night of September 26/27, 2004 at the Cerro Tololo Inter-American Observatory. The instrument "T2" is a 35-cm reflecting telescope equipped with the combined MASS-DIMM detector. The exit pupil is shared between the DIMM channel (two 10-cm apertures) and MASS channel (4 concentric apertures, outer diameter 8.6 cm). Images of the two diffraction-limited spots are taken with a ST-7 detector working in the drift-scan mode, so that only 1-dimensional scans integrated along columns result. Each scan is taken with 5 ms exposure, the 6000 scans are registered continuously in a single "frame" and then processed to extract the seeing.

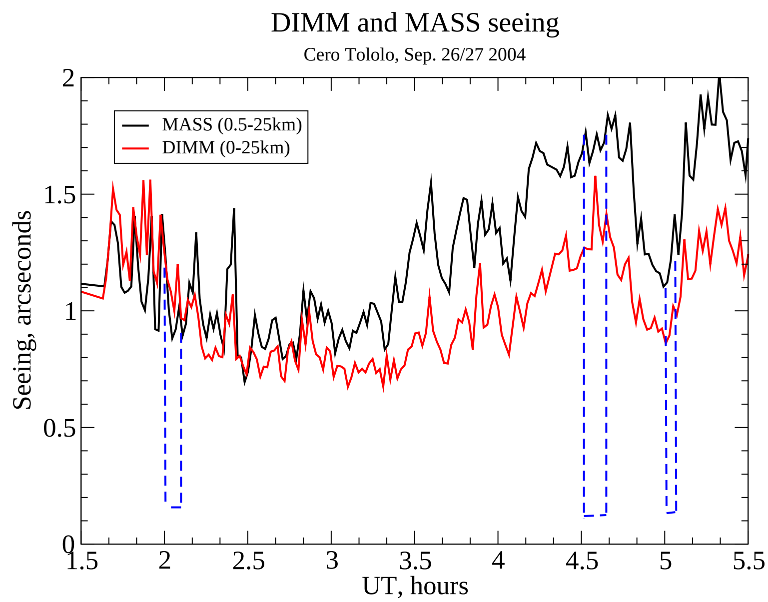

Figure 2: Seeing measured by MASS and DIMM at TMT T2 on September 26/27 2004. The three periods where image profile has been analyzed are indicated by dashed lines.

In Fig. 2 a fraction of the data is plotted against the universal time UT. The sky was clear during this period (a cirrus cloud appeared later). At the beginning of this period, DIMM and MASS demonstrate good agreement, presumably because the turbulence in the first 500 m, not sensed by MASS, was weak. Then MASS begins to overshoot after 3h UT. Both MASS and DIMM use the same telescope and look at the same star. The star was changed at 4:20, with no apparent effect on the data except a small gap.

In Fig. 3 the evolution of the turbulence profile (as measured by MASS) and the scintillation indices in the MASS apertures are plotted. The turbulence at intermediate altitudes was very strong, causing saturated scintillation in the smallest MASS aperture A (2 cm diameter).

During the same night, another two MASS-DIMM units were operational at Cerro Tololo in close proximity to T2. The results from all independent MASS and DIMM instruments agree between themselves very well (better than 5% relative). Thus, we are certain that both MASS and DIMM worked correctly and that the overshoots are not related to any hardware malfunction.

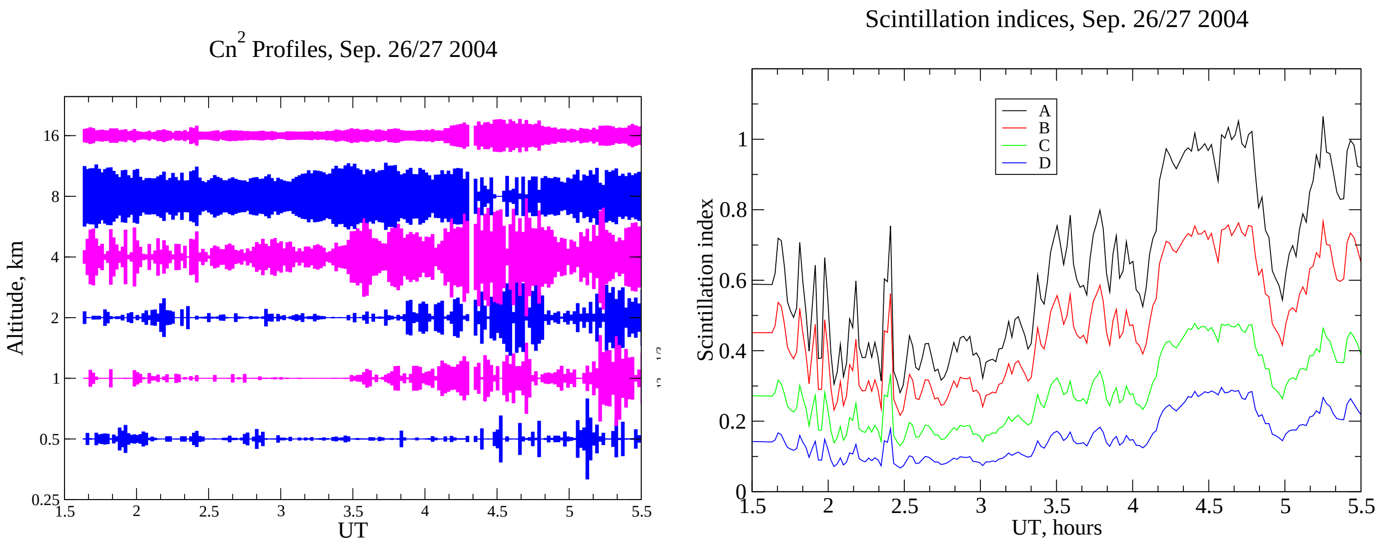

Figure 3: **Left:** Turbulence profile evolution on September 26/27 2004. **Right:** Scintillation indices in MASS apertures.

2 Analysis of the image width in DIMM

If turbulence spatial spectrum is different from the Kolmogorov one, that could explain the overshoots by excess of cm-scale perturbations. Such spectrum was actually measured in early atmospheric studies (Hill, Clifford). However, the existence of optically significant small perturbations would manifest itself in the shape of stellar images registered by DIMM, they will become wider than expected. Hence we study here the profile of spots in the DIMM instrument during three representative periods of the September 26/27 night.

A total of 13 DIMM images was recuperated, each image containing 6000 1-dimensional scans. The images in ST7 format were read by the IDL program `read_st7_image.pro` (Matthias Schöck). Then, using a procedure `avprof1.pro`, we isolated two 25-pixel (19.5″) portions of each scan that contained the left and right spots, respectively. The original 0.78″ pixels were re-binned into 4-times finer grid, with interpolation. Each spot was re-centered (with a simple center-of-gravity) and the 5500 scans (the first 500 scans were ignored) were co-added with integer shifts to the nearest “fine” 0.2″ pixel. In the subsequent analysis we averaged also left and right spots, yielding 13 1D scans of 19.5″ length. Examples of these average scans are given in Fig. 4. We also analyzed 2 images from the pervious night September 26/25 that corresponded tp good seeing.

Modeling of the average scans was done in the framework of the standard turbulence theory (program `model.pro`). We computed the Optical Transfer Function (OTF) as the modulus of the normalized 1D Fourier Transform (FT). The minimum value of each scan has been subtracted prior to FT. This procedure results in the cut of a 2-dimensional OTF along one coordinate axis. Thus, the measured OTFs can be directly compared to the 2D theoretical models.

The pixel scale in the FT plane was computed as $\lambda/(N_{grid} * \alpha$, where $N_{grid} = 128$ is the size of computational grid, $\alpha = 0.195''$ is the size of fine pixel in the image plane, and $\lambda = 530$ nm is the effective wavelength. Such scaling gives the distance in the pupil plane. In fact the CCD detector is sensitive in a

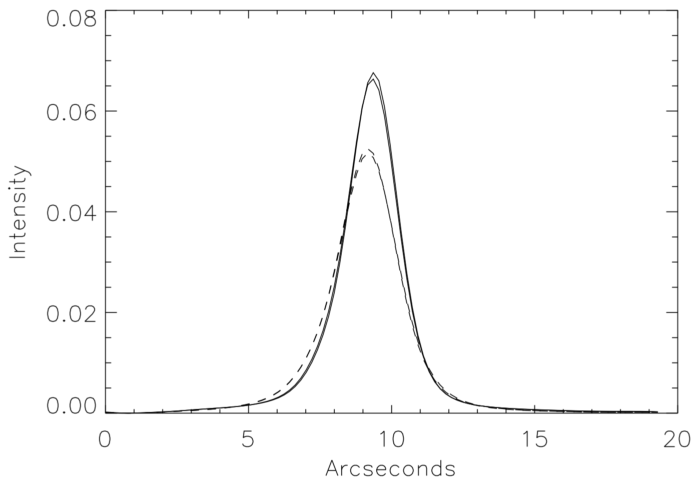

Figure 4: Average re-centered profiles of images 0 and 1 (02:02 UT, full line) and images 9, 10 (04:37 UT, dashed line).

wide wavelength band, causing a non-sharp cutoff due to diffraction. The particular value of λ was adjusted for good agreement with data under good seeing. We also multiplied the OTFS by 0.97 to compensate for the truncation of the scans that affects the OTF normalization.

In the absence of turbulence the OTF is defined by the diffraction on the 10-cm aperture and the smoothing by $0.78''$ square CCD pixels. The measured OTFs are indeed very close to this model T_0 under good seeing, being only slightly affected by the image spread caused by turbulence. The latter is described by the known formula for atmospheric short-exposure transfer function T_a,

$$T_a(x) = \exp[-3.44(x/r_0)^{5/3}(1 - (x/D)^{1/3})], \tag{1}$$

where x is the coordinate in the pupil plane (see above), $r_0 = 0.98\lambda/\epsilon$ is the Fried parameter for the seeing ϵ, D is the aperture diameter.

In Fig. 5 the product $T_0 T_a$ that should describe the observed OTF is computed for the two values of seeing measured by both DIMM and MASS, with a small correction for the airmass (the airmass was about 1.2).

It is clear that the atmospheric model gives a reasonable fit to the observed OTF under $1''$ seeing. The slight differences with the model can be explained by the polychromatic detector sensitivity (uncertain λ), telescope aberrations and noise. However, under bad seeing (and strong scintillation) the OTF is significantly lower than the model. To explain the width of the spots around 04:35 UT, we would have to assume a seeing that is even worse than the "MASS seeing".

The behavior of OTF seen in Fig. 5 for poor seeing is observed in all 6 images taken around 04:30 UT. Thus, it is established that during strong overshoots the spots in DIMM were wider than expected from the measured seeing. This translates to the excess of the wave structure function at cm scales and could indeed explain why MASS over-shoots. This result has been obtained only from DIMM data, without any use of the MASS data.

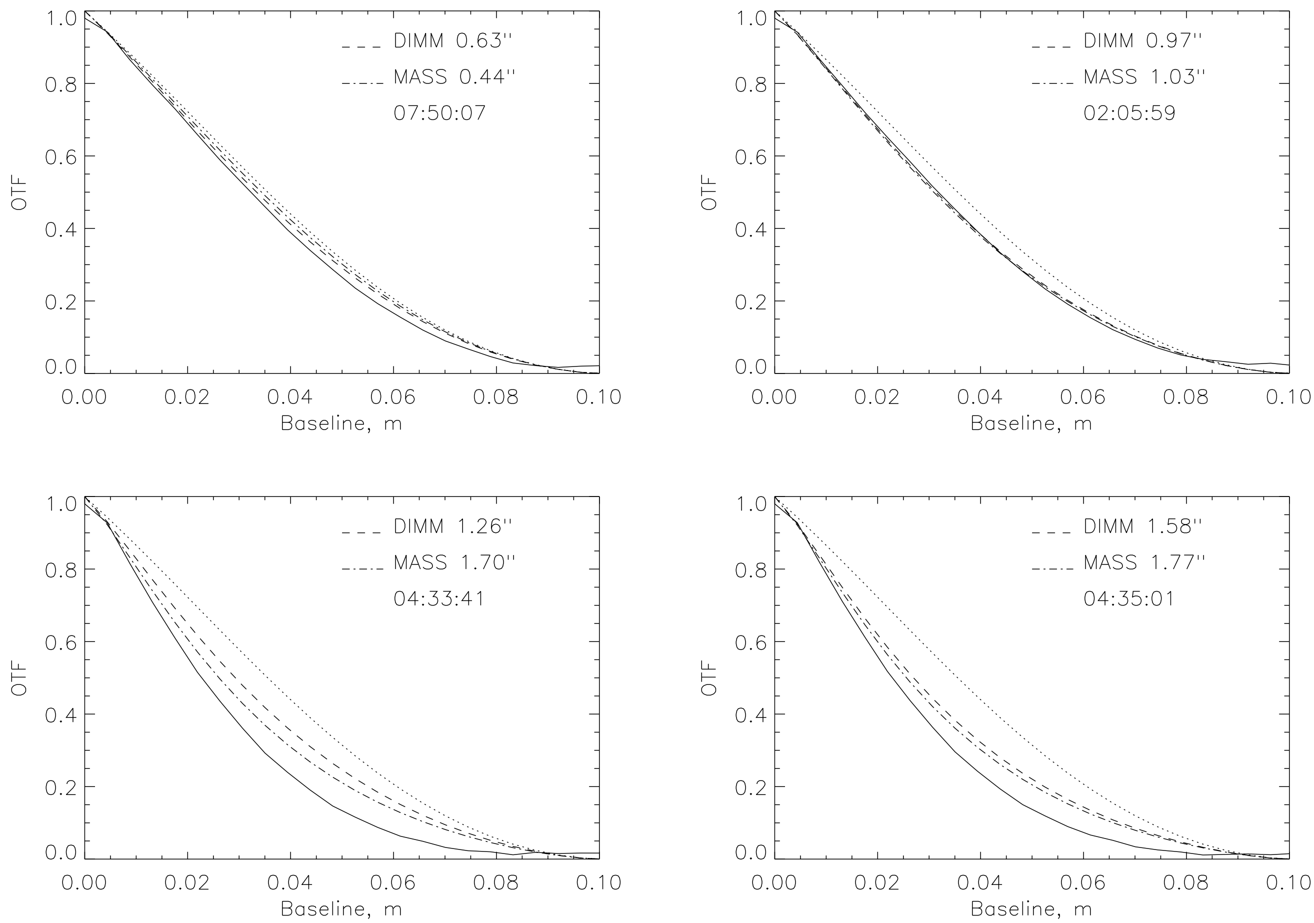

Figure 5: The OTF plots for representative cases without overshoots (top row, 090426 07:50 and 040927 02:50) and with overshoots (bottom row, 040927 04:33 and 04:35). In each plot, the full line is the measured OTF, the dotted line is the turbulence-free OTF, the dashed and dash-dot lines are the model OTFS calculated for the DIMM and MASS seeing (as indicated), respectively.

3 Another night: September 30, 2004

We decided to complement the example with yet another night of overshoots, September 30 to October 1 2004. The same T2 MASS-DIMM instrument is used. The telescope was re-aligned between these nights. Of the two spots, we analyzed the narrowest one (left for Sep 26 and righ for Sep 30). A good match of the OTF to the diffraction-limited OTF (under good seeing) shows that the residual aberrations were very small.

This night had a very low wind velocity near the ground (< 0.5 m/s) and in the whole atmosphere (< 15 m/s, data for the ESO La Silla forecast). The seeing at the beginning of the night was very good, down to $0.5''$. It degraded later, and overshoots appeared (Fig. 6). These seing spikes are related to turbulence at intermediate altitudes, as on September 26 (Fig. 7). The wind velocity at these altitudes was

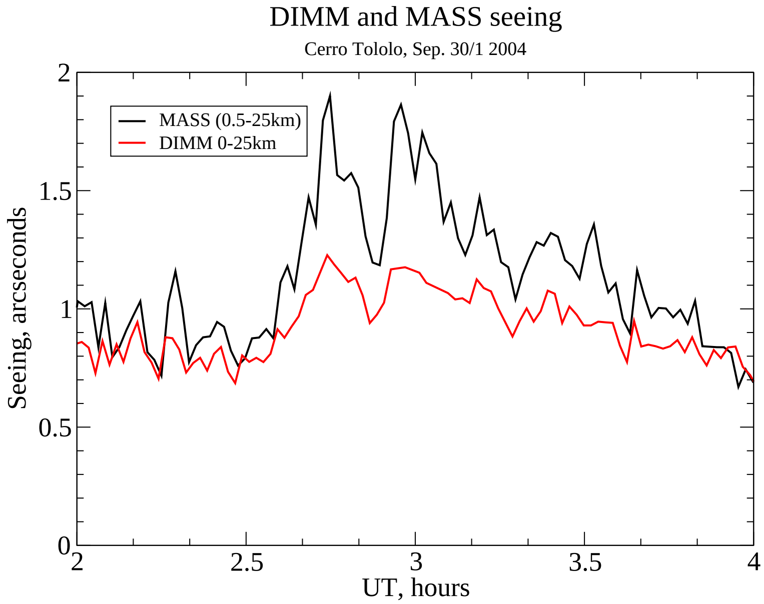

Figure 6: Seeing on September 30/1 2004.

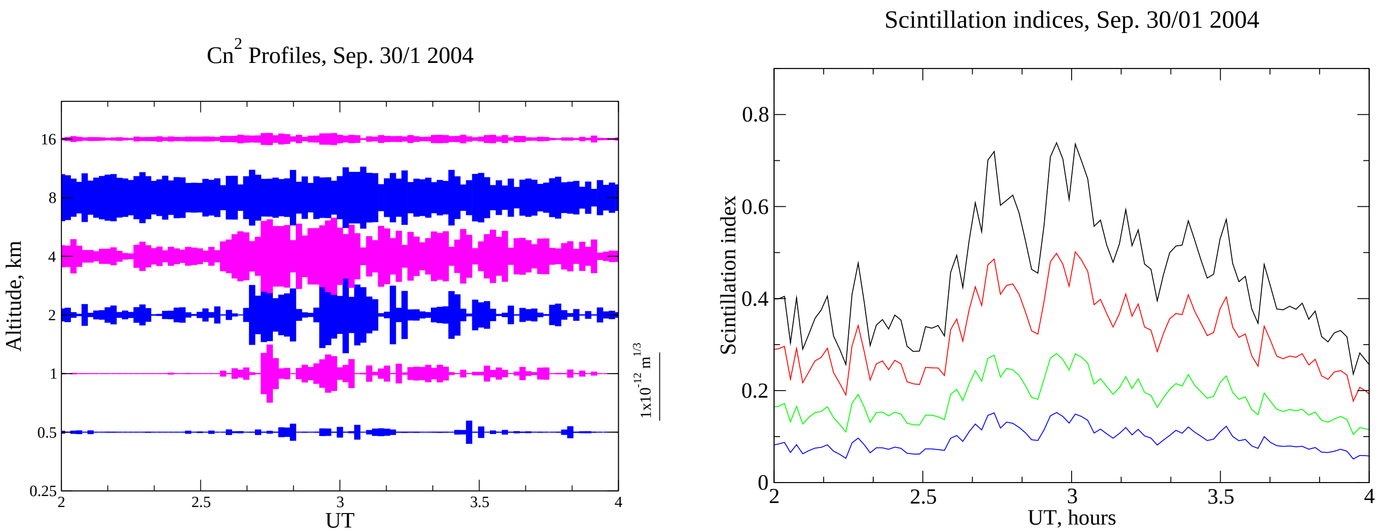

Figure 7: **Left:** Turbulence profile on September 30/1 2004. **Right:** Scintillation indices in MASS apertures for the same night.

unusually low. The scintillation indices were smaller than on September 26. The sky was perfectly clear.

The analysis of the spot profile in DIMM (Fig. 8) shows that it corresponded to the atmospheric model. So, the overshoot around 3h UT was not accompanied by any significant deviation of turbilence spectrum from the Kolmogorov model at cm scale. Moreover, the seeing as measured by MASS would enlarge the spots beyond their actual size. Thus, it is clear that DIMM did not under-estimate the seeing.

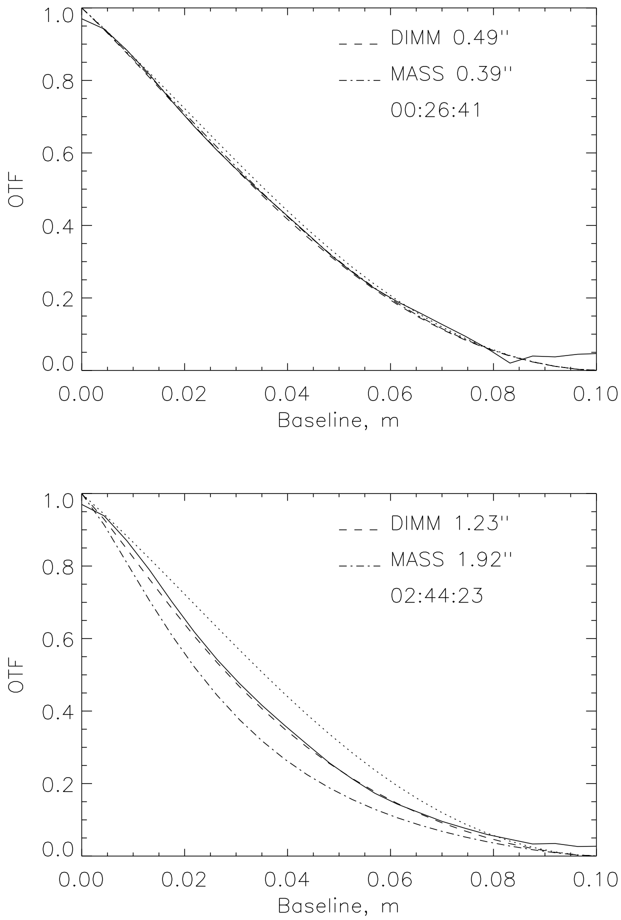

Figure 8: The OTF plots for the night September 30/1 2004. Same notation as in Fig. 5.

4 Possible causes of over-shoots

The problem of over-shoots is not yet solved. The list of possible causes is given below to guide the future work.

- Strong scintillation and the failure of Rytov approximation.
- DIMM under-estimates seeing because of the propagation (turbulence in the far field, less image motion compared to near field).
- The turbulence spectrum is non-Kolmogorov, with excess perturbations at centimetric scales. May be caused by special atmospheric conditions and/or humidity fluctuations.
- MASS over-estimates the scintillation indices because it over-corrects for exposure time under high-wind (fast scintillation) conditions.

- The linear formulas used to compute the scintillation indices in MASS software do not work properly under strong scintillation.

It is very likely that several of the listed factors act jointly and cause the over-shoots.