The verification of the MASS spectral response

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Introduction

The paper[1] shows that the weighting functions (WF) used for turbulence profile restoration from the scintillation indices depend on the spectral distribution of the light incoming on the MASS detector. This spectral distribution is defined both by the energy distribution in the target star's spectrum and by the spectral response of the detector, i.e. by the central wavelength λ_0 and the effective spectral bandwidth $\Delta\lambda$. The uncertainty of the spectral response produces errors in the WFs and leads to the systematic errors in the restored turbulence profile.

The present paper studies possible sources of uncertainty in the MASS spectral response. A recommendation is given on how to reduce the systematic errors of profile restoration in the future and how to correct the data already obtained.

Why the problem exists?

The MASS device includes several optical elements on the path of the incoming light:

- the feeding telescope — either a Cassegrain system or, more often, a Schmidt-Cassegrain,
- the Fabry lens — one or two achromatic lenses with visual AR coatings,
- the segmentator — protected aluminum coating,
- the re-imaging mirrors — protected aluminum or multilayer dielectric coating.

The transmission of these elements together with the spectral sensitivity of the R7400 PMT with bialkali photo-cathode defines the real photometric band of the MASS device. The atmospheric extinction influences the response, too.

The original MASS device had a photometric band that was formed by the PMT sensitivity and the dichroic beam-splitter (directing red light to the viewer) on the red side and by the cut-off yellow filter like Schott GG420 on the blue side. The transmission features of other optical elements are of little significance.

During progressive development of MASS/DIMM devices, several modifications have been made to boost the efficiency. For example, the few first instruments had re-imaging mirrors coated by multilayer films and included the cut-off filter like GG 455 glass. For these devices, the photometric band was close to the standard photometric V-band but total the transmission was low.

At this point we had two alternatives — either to have a well-defined blue cutoff of the MASS spectral band and low light signal, or to get a higher signal and some uncertainty in the spectral band. The second option was chosen, since there is always a possibility to determine or refine the spectral response, whereas the noisy data can not be corrected.

Following this decision, the cut-off filters were removed from the devices. The signal increased significantly (for some feeding telescopes). But when the special element blocking the blue light was removed, the blue cutoff became strongly dependent on the UV transmission of other optical components. It seems that these elements do not have any strong depression in the UV transmission

[1] Tokovinin A. Polychromatic scintillation. JOSA(A), 2003, V. 20 pp. 686-689

or reflection coefficients. In this spectral domain, the main factor are the AR coatings optimized for the visual. The typical behaviors are shown in Fig. 1 for the coatings from Edmund Optics.

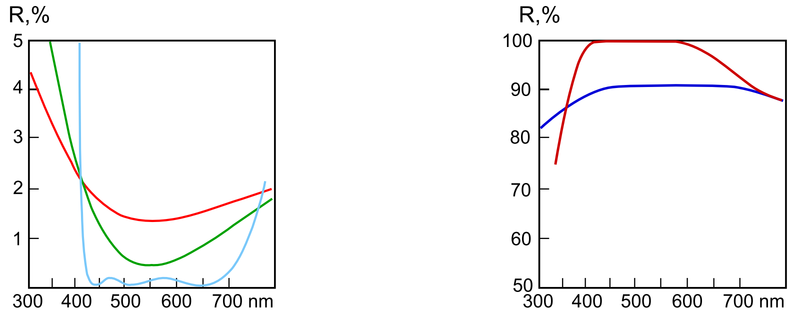

Figure 1: Reflectance of a refractive surface with AR coating (on the left). Red curve — MgF_2 film on BK7 glass, green — MgF_2 on SF5 glass, blue curve — enhanced multilayer coating for visual light. On the right — reflectance of Al layer without AR (blue) and with visual AR coating (red).

For example, the ESO MASS/DIMM device with the C11 telescope has 4 reflective and 6 refractive coated surfaces. These surfaces depress greatly the spectral response below $\lambda < 400$ nm. The absorption in the SF5 glass and in the optical cement in the achromatic lens dominates in the $\lambda < 350$ range.

We can not compute exactly the whole MASS and telescope transmission in the region $\lambda < 400$ nm because many factors are poorly known. Only crude estimate is possible. The direct measurement of the spectral transmission of the device is a separate problem that requires a considerable efforts and a special equipment.

Photometric response curves of various MASS devices

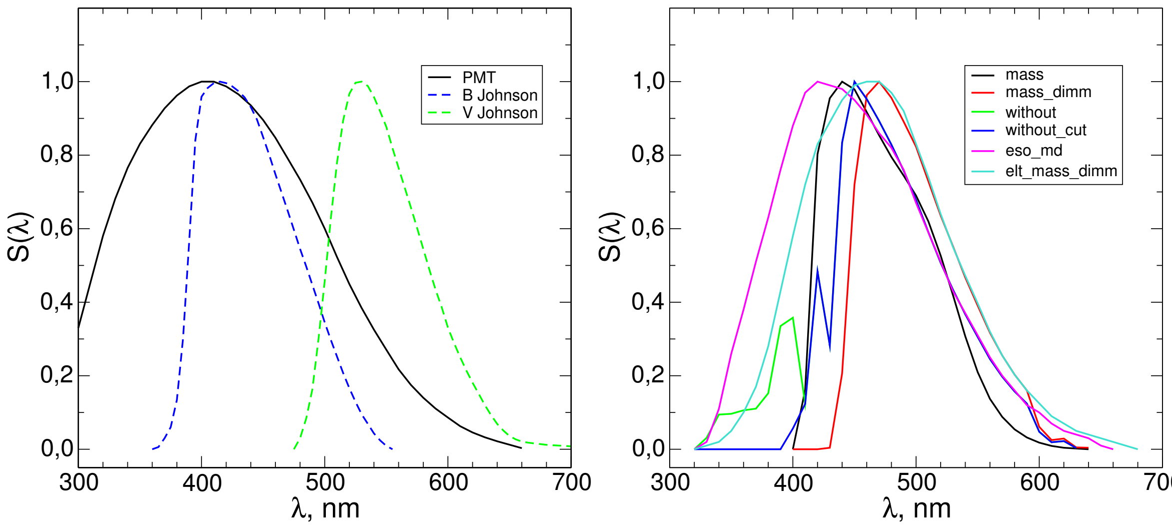

Figure 2: On the left: Photon spectral sensitivity of the PMT R7400 from Hamamatsu and the standard photometric bands B and V. On the right: The collection of the MASS spectral response curves.

The spectral responses for the different versions of the MASS device are shown in Fig. 2. The curve `mass` corresponds to the original MASS that was produced in 3 copies. The curve `mass_dimm` is defined for the MASS/DIMM with a yellow cut-off filter and the re-imaging mirrors with multilayer (green) coating. The same devices without filters have the responses `without` and `without_cut`. The latter curve includes the additional UV light losses due to the feeding telescope and the device optics.

The curve `eso_md` characterizes the MASS/DIMM devices with aluminum coated re-imaging mirrors and typical device optics, but without the contribution of the feeding telescope. It may be useful when the device is installed on a pure Cassegrain telescope without visual optimization. On the contrary, with a Schmidt-Cassegrain telescope optimized for visual observations (like Meade and Celestron telescopes), the `elt_mass_dimm` is more adequate.

The integral characteristics of the photometric response for the existing versions of the MASS device are listed in the Table 1.

Table 1: Integral characteristics of the response curves of the MASS devices. λ_0 — central wavelength, λ_{eff} — effective wavelength for A0 V stars, $\Delta\lambda$ — effective bandwidth (integral under the curve). All values are shown in nm.

Version	λ_0	λ_{eff}	$\Delta\lambda$	Comment
`mass`	475	469	103	Original MASS
`mass_dimm`	501	496	94	Yellow filters, green mirrors
`without`	474	470	99	Green mirrors, TMT telescope
`without_cut`	486	479	88	Green mirrors, Meade telescope
`eso_md`	455	453	157	Al mirrors, no telescope
`elt_mass_dimm`	474	467	149	Al mirrors, C11 telescope

Note that we always use the photon spectral response, not the energy response. Therefore the energy distributions in the stellar spectra must be in photons, too.

Quantitative estimation of the effect

First, I studied the changes in the WFs produced by the changes in the central wavelength and bandwidth using model Gaussian-like response curves. The shift to the blue increases the WFs, the widening depresses the WFs at high altitudes. The over-estimated WFs lead to an under-estimated turbulence intensity while the WF depression at high altitudes results in the apparent increase of the turbulence altitude.

For the quantitative analysis of possible systematic errors induced by the incorrect choice of the spectral response, I use the real curves from Table 1. I designate the set of WFs corresponding to some photometric response as WF(band). The energy distribution for B0 V star is used because 1) such spectrum produces the maximum effect and 2) such stars are frequently chosen for measurements. In Fig. 3 (bottom) the effect produced by the shift of 20 nm to the red is illustrated. One can see that the WFs for normal indices are changed by no more than than 5%, the WFs for differential indices are changed by up to 10%. The use of a red-shifted response will overestimate the turbulence integral by $\approx 10\%$ and will lead to a small underestimate of the layer's altitude.

The upper part of Fig. 3 shows the ratio of the WF(`eso_md`) to WF(`mass_dimm`). These curves differ significantly in their positions and width. Here the differences of the WFs reache 30% for differential and 15% for normal indices. Note that the effect can be reversed, depending on the dominating layer altitude. The complex changes of the WFs for different indices caused by the error in the spectral response will likely increase the residuals in the profile restoration.

The WFs for `without` and `without_cut` spectral responses have maximum difference as large as 25% in the case of AB index. For normal indices, the difference is less than 3%. Similar differences were found in the case of `elt_mass_dimm` and `mass` curves having the same λ_0 but different $\Delta\lambda$.

These examples show the upper limits of possible systematic errors produced by using a wrong

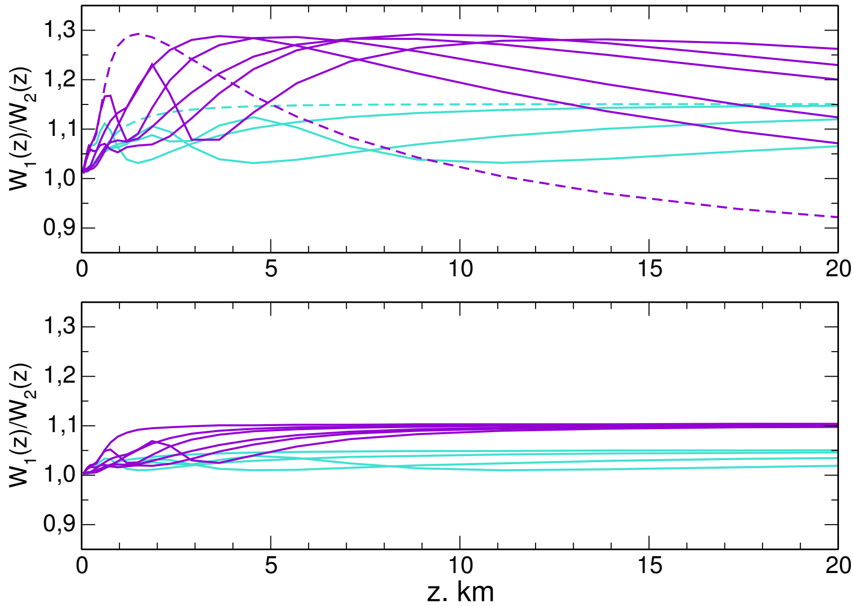

Figure 3: Upper plot: the ratio of WF(`eso_md`) to WF(`mass_dimm`). Lower plot: the ratio of WF(`eso_md`) to WF(shifted by 20 nm `eso_md`). The green curves are the normal indices, the violet curves are the differential ones. The dashed curves correspond to the A and AB indices.

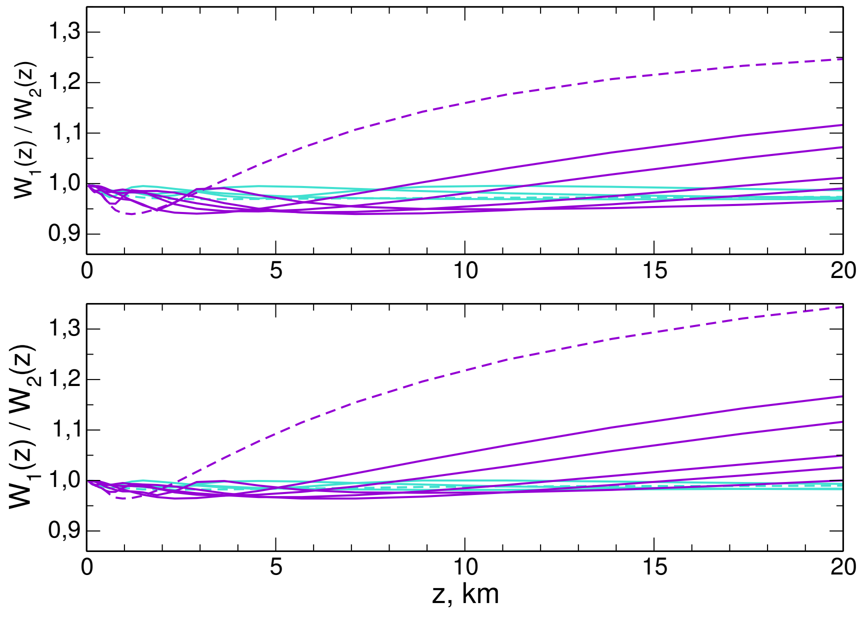

Figure 4: Upper plot: the ratio of WF(`without`) to WF(`without_cut`). Lower plot: the ratio of WF(`elt_mass_dimm`) to WF(`mass`). These bands differ in $\Delta\lambda$ and are similar in λ_0.

spectral response. Similar systematic errors arise when a wrong spectral class of the target star is used. For example, when the spectral type G0 III is used instead of B0 V, the WFs change in a way similar to the wavelength shift of the spectral response.

The systematic error in the the seeing is about half of the WF change, so the error in seeing does not exceed 15% even in the case when the `mass_dimm` curve is used instead of `eso_md`. In the real situation the error is even less because the whole set of the WFs is used during the restoration, not only WF for AB pair. On the average, the difference in seeing for the case of Fig. 4 (bottom) is about 5% in the relevant altitude domain.

For example, the results of turbulence restoration with two different response curves — the correct one `mass` and the incorrect one `elt_mass_dimm`, are presented in Fig. 5. The night of August 26, 2005 at the Maidanak observatory was chosen due to a high altitude of turbulence on this night. The boundary layer turbulence appeared occasionally. When the incorrect curve is used, the measured seeing increases by 5%. The free-atmosphere seeing (above 1 km) is over-estimated by 2% only. The root-mean-square error of the correct/incorrect seeing ratio is about 0.04 and 0.02, respectively.

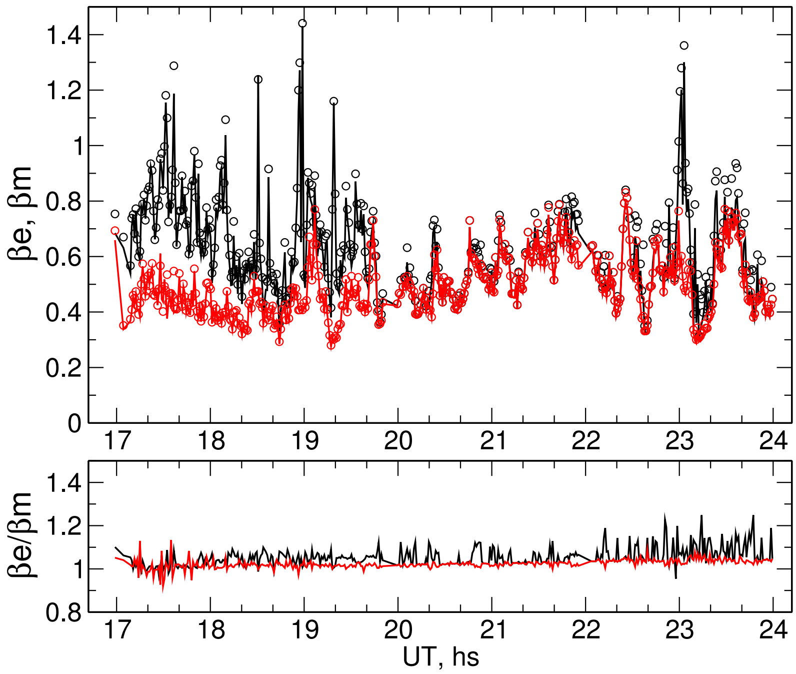

Figure 5: Upper plot: Data of the original MASS device at Maidanak for 2005-08-26. The seeing values β_E and β_M are computed from the profiles restored with the `elt_mass_dimm` (circles) and with the `mass` (line) curves, respectively. Lower plot: the ratio β_E to β_M (black — including the 0.5 km layer, red — without this layer).

Verification of the MASS spectral response

The MASS device is a highly accurate photometer able to measure the stellar flux to about $0\overset{m}{.}001$ –$0\overset{m}{.}002$ under good sky condition. The base of the simplest verification is a comparison between the measured star magnitudes in the instrumental photometric system of MASS m_{MASS} and the catalog magnitudes in the standard photometric system, for example — magnitude V. The difference $m_{MASS} - V$ depends on the catalog color in different ways for different MASS spectral responses. As the problem is mainly related to the spectral region short-ward of 420 nm, the use of the $m_{MASS} - B$ color instead $m_{MASS} - V$ is preferable.

The color equations calculated for all MASS response curves are presented in Fig. 6. All functions are normalized to the A0 V spectral type. One can see that the slope of these curves strongly depends on the MASS response. For the extreme cases `mass_dimm` and `eso_md`, the slope varies from -0.64 to -0.19, depending mainly on the central wavelength λ_0 (see Table 1).

The bandwidth $\Delta\lambda$ affects the curvature of the color equation. For example, the color equation for the `eso_md` deviates down for white stars ($B - V < 0^m.0$) since this band covers the part of stellar spectrum before the Bahlmer jump. Measurements of the B0 – F0 stars permit to estimate $\Delta\lambda$ for a specific MASS device.

The comparison between the color equations for `elt_mass_dimm` and `mass` shows that these equations are coincident for $B - V > 0^m.0$. For B0 stars, $m_{MASS} - B$ for these curves differ by only $0^m.08$. It is not a large difference, therefore special measurements are needed for $\Delta\lambda$ estimation.

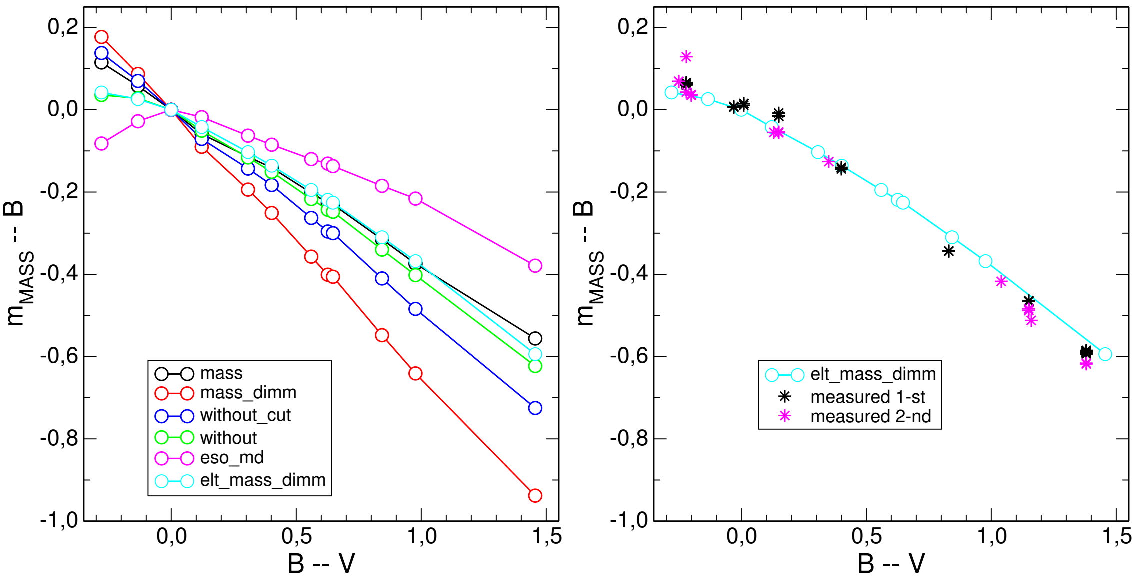

Figure 6: On the left: The calculated color-color diagram $m_{MASS} - B$ vs. $B - V$ for all MASS spectral response curves. On the right: The color equation for the `elt_mass_dimm` (line) and the measurements made with the ESO MASS/DIMM (points).

The proposed method involves the calculation of the color equation from the standard energy distributions. Therefore, the inaccuracies of the input data produce the color correction errors. As this correction can be large, its errors can achieve $\sim 0^m.03$ or more for red stars.

The situation is complicated by the fact that about 30% stars in the MASS catalog are variable. Thus, among the 12 target stars measured at Tolar in 2004 – 2006, six stars are known to be variable with amplitudes from $0^m.01$ to $0^m.3$. Moreover, the photometric data for bright stars are less accurate than for the fainter stars. However, the problem of establishing the spectral response is simplified by the fact that the bandwidth and the central wavelength are strongly related. It is easy to see this in Fig. 6. This relation may be slightly distorted by the additional cutoff in the red, as in the case of `mass` and `without_cut`, but these cases are not problematic.

A practical method of the spectral response measurement is presented in the Appendix.

Experimental tests.

The first special measurements were accomplished by M. Sarazin during the ESO MASS/DIMM tests at La Chira. On the nights of August 2 and 3, 2006, 12 specially chosen stars were measured, for 5 – 10 minutes each. Note that among the 20 different stars selected from `star.lst`, 7 stars are suspected variables.

The preliminary data reduction included the magnitude correction to the zenith (not outside the atmosphere!) with the typical extinction coefficient of $0^{m}\!.25$. This value is an estimate only, but its error is less than $0^{m}\!.05$, leading to the zenith-magnitude error of less than $0^{m}\!.02$ at the maximum airmass of 1.34. Such procedure gives the response curve which includes the atmospheric transmission component. The restoration method presented in Appendix could not be applied due to the small amount of the measurements and the non-uniform coverage of the color range.

The comparison of the instrumental colors $m_{MASS} - V$ with the calculated color equation shows that the `eso_md` curve adopted as a first approach did not agree with the measurements. To achieve the agreement, the blue cutoff of the response was shifted to the red in several steps, until an agreement was reached. As result, the curve `elt_mass_dimm` was obtained. This curve should be used with the ESO MASS-DIMM.

Similar reduction was applied to the measurements obtained at Tolar in 2004 – 2006. In this case the extinction coefficient was determined from the data itself. It is found to be in the range $0^{m}\!.16$ – $0^{m}\!.20$ (the spectral response of this device is "redder" compared to the ESO device). Unfortunately, these measurements did not contain stars of sufficiently different spectral types. Therefore, only the average slope of the dependence $m_{MASS} - V$ vs. $B - V$ was determined. These results for all the observational period are presented in Fig. 7. On the right-hand side, the two histograms of the slope (one for the period before October 2004, another after) are shown.

To compute this dependence for a given night, the measurements of a star and the next star were used if the difference between their $B-V$ colors exceeded $0^{m}\!.2$ and the root-mean-square flux deviation did not exceed $0^{m}\!.01$ for both. The latter condition guarantees the photometric sky quality, while the first condition decreases the influence of the catalog magnitude errors.

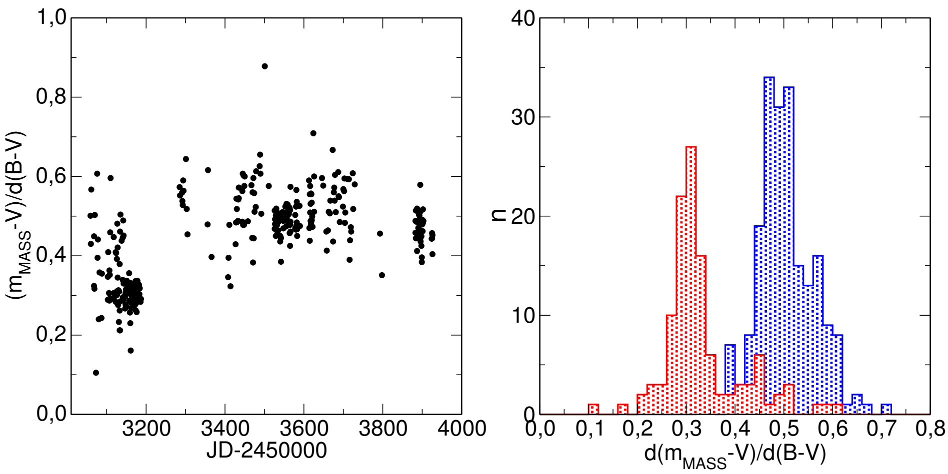

Figure 7: On the left: the slope of the color equation for the MASS-DIMM at Tolar as a function of time (Julian date). On the right: the distribution of the slopes before October 2004 (red, the median is 0.31) and after (blue, the median is 0.50)

Since it is known that the multilayer re-imaging mirror are used in the Tolar device, we conclude what the device spectral response matched the `mass_dimm` curve before October 2004 and the `without_cut` curve after that date.

Conclusion

This study shows that in order to control or improve the knowledge of the MASS spectral response and to avoid the turbulence profile bias caused by the poor knowledge of the response, a short special program of photometric measurements (one half night per season) must be included in the overall schedule. A special list of the stars with brightness $4^m_. \div 5^m_.$ is needed for such measurements. Such stars have more precise catalog magnitudes than the normal (brighter) MASS targets. The number of stars must be sufficient to exclude all suspected variable stars and to optimize the distribution of the colors. During the program execution, the stars at airmass $M_z \approx 1.0$ will be measured for the color equation and stars at $M_z \approx 1.6$ will be measured to define the extinction coefficient.

The use of a supplementary cut-off filter with the boundary at $\lambda \approx 380$ nm will give a more reliable and precise result. In this approach, the difference between the fluxes with and without such filter will be small and will be measured with high accuracy. The catalog magnitudes are not needed at all. Unfortunately, this procedure can not be carried out remotely. After finishing the measurements, the filter may be left in the device in order to fix the blue cutoff and to eliminate the need of such measurements in the future.

For the new devices, the installation of such filter is very desirable. The commercially available filter GG385 from Schott with thickness 3 mm and diameter 25 mm can be obtained from http://www.pgo-online.com/intl/katalog/schott.html, for example. It is possible to insert the filter together with the Fabry lens.

A. Photometric band determination with minimal assumptions

The proposed procedure uses the fact that unknown (or poorly known) features of the spectral response curve are associated with its blue cut-off. The behavior of the spectral response at the red side is defined by the spectral response of the PMT and is considered as *a priori* known. The blue slope of the response is modeled by a simple formula:

$$s(\lambda) = \exp\left(-\frac{(\lambda-\lambda_c)^4}{r^4}\right) \text{ for } \lambda < \lambda_c, \qquad s(\lambda) = 1 \text{ for } \lambda \geq \lambda_c. \tag{1}$$

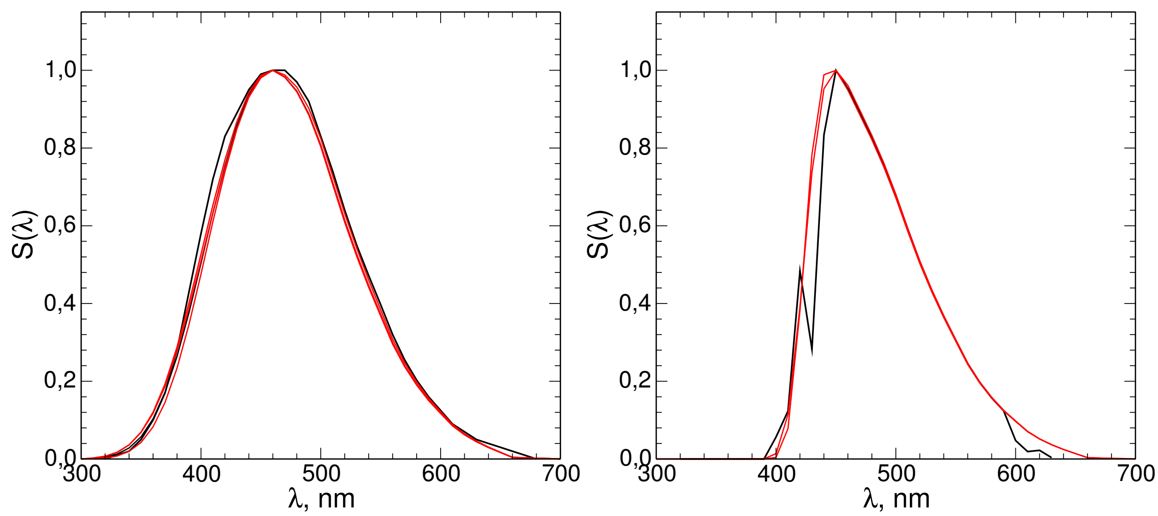

Figure 8: On left: the original curve `elt_mass_dimm` used to compute the simulated colors $m_{MASS} - B$ (black) and a few response curves restored from these colors with different noise realizations (red). On right: the same for `without_cut`.

The function under the exponent is the dependence of the absorption coefficient on λ in the blue region. For most optical glasses, the absorption coefficient near its sharp growth is approximated well by the bi-quadratic function. The formula (1) gives the un-normalized dependence, but it is of no importance because the normalization will be included in the zero-point.

Hereafter the problem is reduced to the calculation of the 3-parameter dependence $CI = m_{MASS} - B$ on $B-V$, where the third parameter is the zero-point CI_0 which shifts the $CI(\lambda_c, r)$ curve vertically. Using a minimization procedure, a set of the parameters that fits the measured instrumental colors can be found. For the minimization, a C-module pluggable into **xmgrace** was written, and the determination of the CI_0, λ_c, r has been accomplished with the help of `Data/Transformation/Non-linear curve fitting` function of **xmgrace**.

In the absence of real data, I tested the method by numerical simulation. For the `elt_mass_dimm` curve, I calculated 12 points of the color equation $m_{MASS} - B$ and added random noise with an amplitude of $0\overset{m}{.}02$ to each point. The results of the parametric restoration are presented in Fig. 8. One can see that the spectral response was well restored. Note that the `elt_mass_dimm` curve was defined earlier by the iterative method, therefore it is not very well described by (1).

The simulation for the `without_cut` curve with sharp details have been done as well. The smooth response curve was obtained. The $0\overset{m}{.}02$ noise does not affect the restoration of the spectral response. However, when the noise is increased to $0\overset{m}{.}05$, the restoration becomes unstable.

A comparison between the WFs for the initial response with the WF for the restored response shows that in the first case the difference does not exceed 2.5%, and in the second case it is less than 10%. The larger difference for the `without_cut` curve is explained by its specific shape. This explains also why the restored values of $\lambda_0 = 486$ nm and $\Delta\lambda = 106$ nm differ from the true (input) values.