

Planet scintillation as a probe for ground-layer turbulence

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Version 1. December 8, 2004 (saturn.tex)

1 Introduction

The MASS instrument measures scintillation indices (normal and differential) in 4 concentric apertures. From this data, the vertical distribution of turbulence (profile) is restored. With stellar source, the vertical resolution is $\sim 1/2$ of the altitude, and usually 6 fixed layers from 0.5 to 16 km are fitted to restore the profile.

Scintillations from a planet is mostly produced by low-altitude turbulence because the contribution of high layers is diminished by spatial averaging. Thus, it should be possible to increase the vertical resolution of MASS in the first kilometer above ground by observing planets. To distinguish this method from MASS, it is called Planetary Scintillometer, or PlaSci. Here I describe first tests of this idea conducted in November-December 2004 during the SLODAR campaign at Cerro Tololo.

2 The weighting functions

The weighting functions (WFs) – dependence of scintillation index on the distance to a turbulent layer – are computed for a planet in the same way as for stellar source, using the formulas for polychromatic scintillation from JOSA(A), 2003, V. 20, p. 686-689, with an additional term under the integral that describes the spatial averaging due to source size. The source is modeled as uniform disk of angular diameter θ , the additional term is then $[2J_1(2\pi f\theta z)/(2\pi f\theta z)]^2$, where z is the distance to the layer (range), f is the modulus of the spatial frequency (one over period). The IDL program is `chromext.pro`, driven by `planetweight.pro`.

Figure 1 shows the weighting functions for normal and differential indices corresponding to the conditions of our experiment. Analysis of the formula for weighting functions shows that planetary scintillation is mostly determined by geometrical optics because the spatial smoothing length always exceeds the Fresnel radius $\sqrt{\lambda z}$. At low altitudes the smoothing is set by the aperture size d . At high altitudes the smoothing length is θz , where θ is the angular diameter of the planet and z is the range. Thus, WF reaches maximum roughly at a range $z \sim d/\theta$. This purely geometrical condition is different from the diffraction equation $\sqrt{\lambda z} \sim d$ that applies to stellar scintillation in MASS.

The above consideration leads to two important conclusions. First, to cover a large range in altitude, a correspondingly large range in aperture diameters in PlaSci is required. Second, at lowest altitudes the WFs of all apertures are similar and proportional to each other. Scintillation produced by the near-ground turbulence depends quadratically on the range. This circumstance is very unfortunate because usually near-ground turbulence is a decreasing function of altitude. The contribution of the lowest layers to planetary

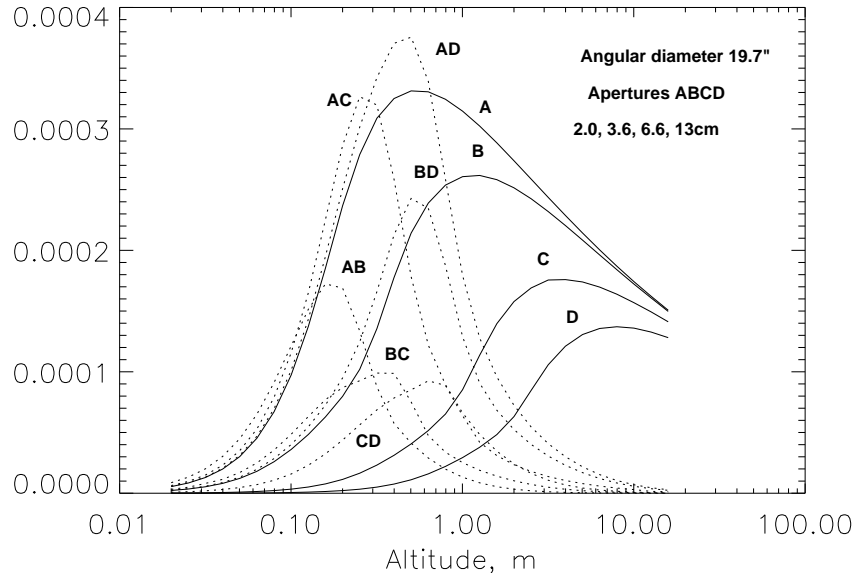


Figure 1: Weighting functions for four apertures A,B,C,D and their pairwise combinations for the conditions of the experiment. The horizontal axis is the range in km (not m as shown).

scintillation thus remains always uncertain, precluding their reliable measurement. Of course, a generalized regime can be used to “shift” these layers and make them measurable.

It is clear from Fig. 1 that even raw scintillation indices can serve to evaluate turbulence intensity. The AB index isolates turbulence at ~ 200 m from the instrument, the BD index corresponds to the range ~ 500 m, and the indices C or D measure the contribution of high layers. I selected those 3 indices and extracted the corresponding turbulence integrals in these “fixed layers”.

Planets are often seen at low elevation above horizon, as was the case during this experiment. The results have to be corrected for the zenith angle γ or airmass $a = \sec \gamma$. I divided the turbulence integrals and ranges by a to reduce the measured quantities to standard, zenith-viewing condition. With a typical airmass $a \sim 2$, the lowest fixed layer corresponding to AB index is sensitive to turbulence at altitude about 100 m.

3 Equipment and data

Planetary scintillation has been measured with the first (prototype) MASS instrument installed in the USNO dome at Cerro Tololo. The advantage of this instrument is its large range of aperture diameters, from 2 cm to 13 cm. To avoid saturation of photon counts in the largest aperture D, I installed a neutral density filter that reduced the flux by ~ 3 times. Other apertures remained without filters.

The visibility of suitable planets in November-December 2004 was poor, limiting the choice to Saturn. Unfortunately, the ring was at maximum opening (26°) and contributed some 25% of the total flux. So far, I neglected the ring in the data reduction, assuming the planet to be a uniform disk of $19.7''$ diameter.

Saturn was visible starting from 5h UT and culminated near sunrise at airmass around 2. Jupiter was also visible at large airmass before sunrise. Some data on Jupiter have been recorded but they are not used here.

These experiments were conducted during the campaign of SLODAR testing [Ref. SLODAR Report]. SLODAR is an instrument developed for detailed measurements of turbulence in the first kilometer above ground. Its vertical resolution was around 150 m. Turbulence profiles with lower resolution were measured by a combination of MASS and DIMM instruments (T3 unit of the TMT site-testing campaign). The data from an acoustic sounder (SODAR) were also obtained, but they are not used here.

Scintillation of Saturn was recorded on 4 half-nights: November 24, 26, 30 and December 1 (evening dates) 2004. Typical relative error of scintillation indices in 1-min. accumulation is around 5%.

4 Profile restoration from planet scintillation

Standard MASS restoration technique consists in fitting the observed scintillation indices to the model of 6 thin layers at fixed altitudes or 3 “floating” layers with arbitrary altitudes. I adapted these two strategies to PlaSci.

The measured scintillation indices are small, rarely reaching 0.001. The 4-digit accuracy of the index data in the MASS output files is insufficient for our purpose. Thus, the indices were re-calculated from the raw statistical-moments (.stm) files using the awk script `stm2indold.awk`. The results (UT, A,B,C,AB,... indices) are placed in files YYDDMM.ind. Data on single stars and Jupiter are erased manually from these files.

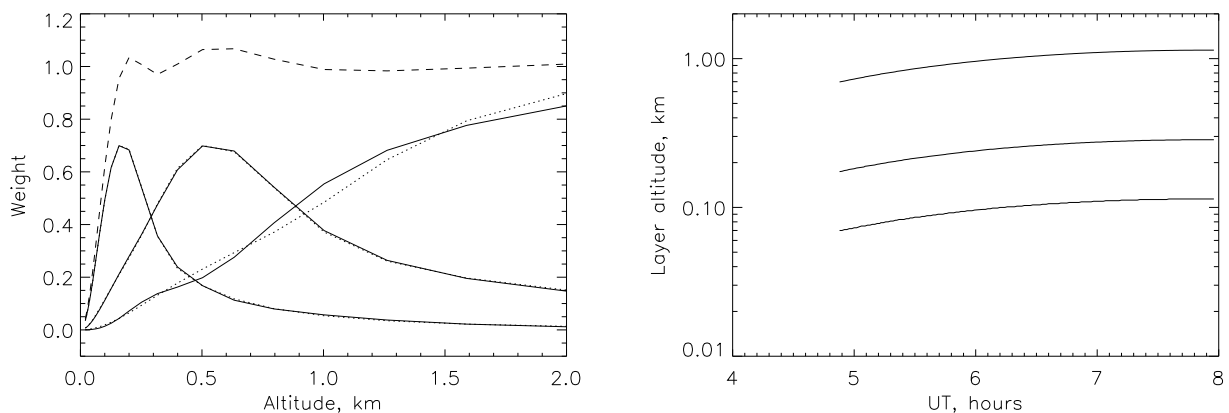


Figure 2: Left: Effective sensitivity of three “fixed” layers versus range (full lines) and the sum (dash), showing near-constant response above 100 m. Right: Effective altitudes of 3 fixed layers vs. time on Dec. 1, 2004.

The “fixed layers” method is based on the indices in apertures AB, BD, and C. These “natural” response functions, shown in Fig. 2, isolate 3 layers at ranges of 200 m, 500 m and 1.5 km (and higher). The altitudes, corrected for the air mass, are ~ 2 times lower. The restoration program `saturn2.pro` takes the experimental scintillation indices and uses the weighting functions pre-computed by `planetweight.pro` and saved in `saturn.idl`. The results of this restoration are saved in an ASCII file `satwMMDD.dat`, MMDD

being the month and evening date of the observation. The columns of this file contain UT, total seeing, airmass, zero, turbulence integrals in 3 layers (units $10E-13 \text{ m}^{1/3}$) and three altitudes (in km). All data are corrected to zenith.

The floating-layer approach is implemented in `float3a.pro`, again with pre-computed weights. The logarithmic altitude grid for weight computation is selected, starting at 20 m and up to 16 km, with 30 steps. Thus, each step corresponds to altitude change by 1.25 times. For each combination of 3 ranges selected from this grid, the program restores the intensities of 3 layers by a simple matrix inversion. Some negative intensities resulting from this procedure are set to zero. The altitude combination that best matches the data (indices) is selected as a result. The results are saved in files `satMMDD.dat`. The format is similar to the fixed-layer results, except that the 4-th column now contains χ^2 measure of the fit quality (assuming 5% uncorrelated errors on indices).

I found that the lowest layer has a tendency to be selected at the bottom of the altitude grid. This produces unstable results because a small change in the low-layer range results in a large change in the “restored” turbulence intensity. Thus, I restrict the lowest-layer range to 50 m or higher.

5 Results

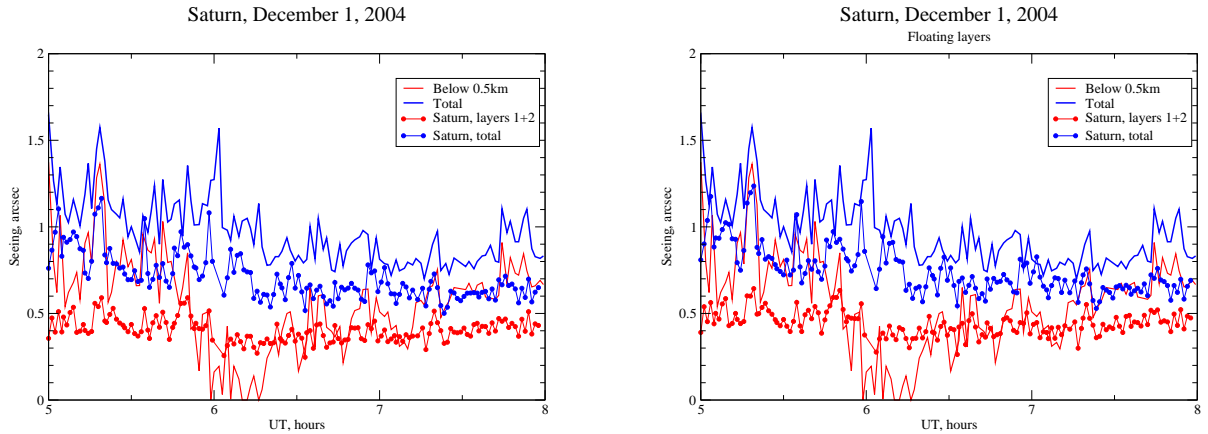


Figure 3: Comparison of turbulence restored from Saturn scintillations (PlsSci, thin lines with circles) with the MASS-DIMM results (thick lines) on December 1, 2004. PlsSci does not sense the near-ground turbulence and thus under-estimates the total seeing. Left: fixed-layers method, right: floating-layers method.

As an example, I show in Fig. 3 the comparison of seeing measured with PlsSci and MASS-DIMM. This date is selected because the structure and intensity of turbulence in the first kilometer was highly variable.

It is immediately apparent that both restoration methods give very similar, almost indistinguishable results. Both under-estimate the total seeing because the contributions of turbulence below ~ 100 m and above ~ 2 km are not fully measured. The floating-layers method tends to give somewhat higher turbulence intensity, for a good reason: its lowest layer is typically below 100 m, and its highest layer is placed at the

top of the grid (altitude around 8 km after airmass correction). The altitude of the middle floating layer was around 300 m, i.e. close to the 2-nd fixed layer. However, there was no clear correlation in the altitude variation of the middle floating layer and the descending turbulent layer detected by SODAR and SLODAR between 5h and 6h UT on December 1.

The direct comparison of PlsSci with the MASS-DIMM is difficult. The DIMM minus MASS integral corresponds to altitude weighting that falls to zero around 500 m. Thus, if intensive turbulence is present near ground or at 300-400 m (as was the case on December 1), DIMM–MASS should measure a higher seeing than the 2 lowest PlaSci layers combined. On the other hand, DIMM–MASS under-estimated the ground layer around 6h UT, possibly because of the residual “over-shoot” of MASS.

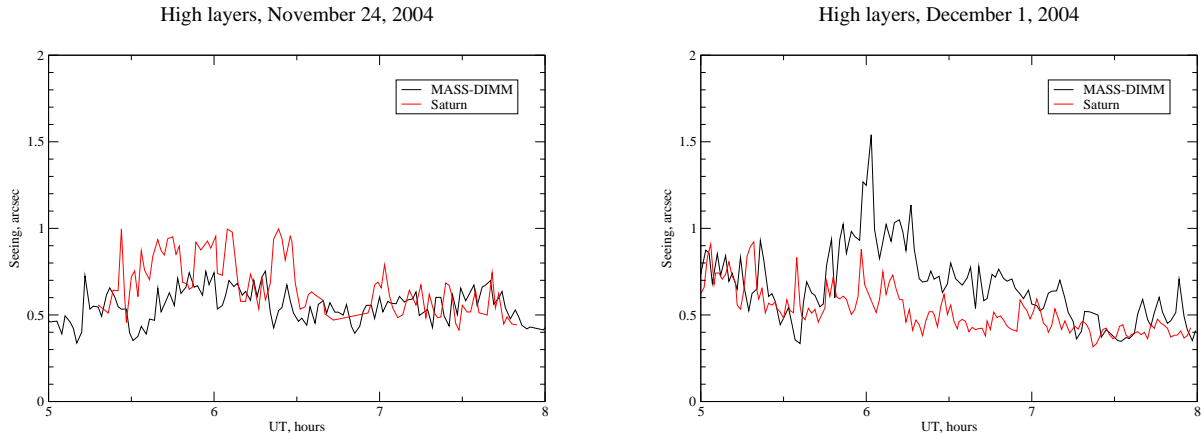


Figure 4: Seeing produced by layers above 0.5km as measured by MASS and by the PlaSci “high layer” on two nights.

There is a good agreement on the intensity of the high layers measured by MASS and by PlaSci (Fig. 4). The agreement was excellent on Nov. 26 and 30. The largest discrepancy occurred on Dec. 1 around 6h UT, when MASS detected a strong packet of turbulence between 1 and 2 km. The MASS data could be a slight over-estimate (as inferred from apparently spurious drop of the ground-layer seeing in Fig. 3), but this turbulence should be well-sensed by the “high” layer of PlaSci because its range was within the broad maximum of the corresponding weighting function.

The relative stability of PlaSci results from one minute to another is a strong indication that its signal is real. As mentioned above, systematic difference with MASS-DIMM is expected because of different altitude weight and also because of possible simplifications in the data reduction (neglect of Saturn rings).

Yet another useful comparison data are provided by SLODAR. Its vertical resolution is about 150 m. In Fig. 5 I compare the SLODAR and PlaSci data for the 2 lowest “fixed” layers, on all four nights. Again, matching the vertical sensitivity of the two instruments is not trivial. I over-sampled the SLODAR profile with 10 m vertical resolution and then selected its portions from $h/2$ to $2h$, where h is the current (zenith-reduced) altitude of the fixed layer. This is a crude approach, but the SLODAR resolution is too low to try something more sophisticated. The SLODAR profiles nearest in time to the PlaSci data are matched in the plots (padded with zeros if no match is found).

On a night of November 24 with a strong near-ground turbulence the agreement of both PlaSci layers

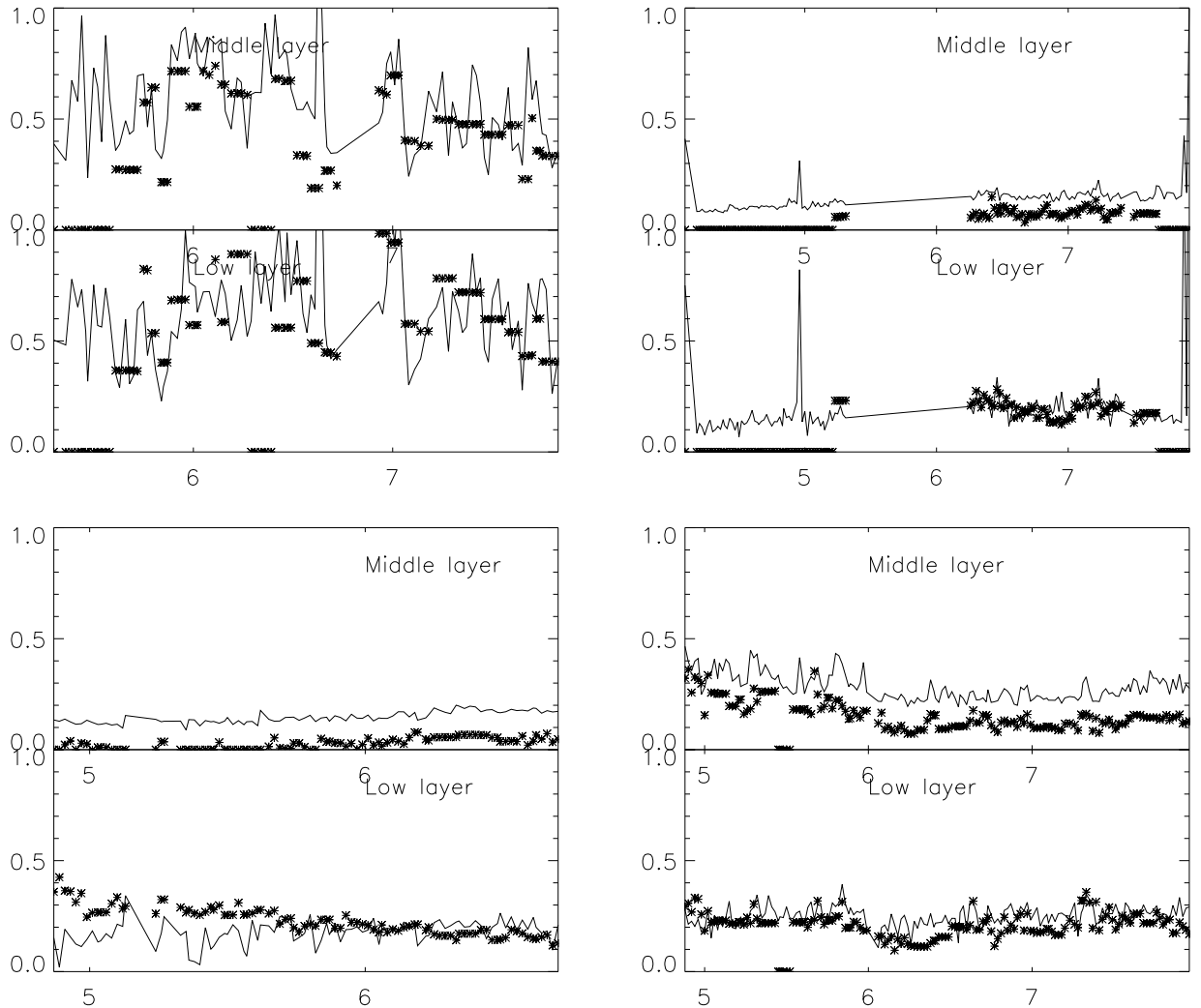


Figure 5: Comparison of turbulence measured by PlaSci (lines) and SLODAR (asterisks). Top to bottom and left to right: November 24, 26, 30 and December 1, 2004. Vertical axis – seeing in arcseconds, horizontal axis – UT in hours.

with SLODAR is impressively good. On the remaining nights, the low layer agrees well, while in the second layer SLODAR always shows less turbulence than PlaSci. This second layer falls in the second resolution element of SLODAR that is known to under-estimate turbulence systematically (often measures negative intensities). This problem is related to the deconvolution procedure in SLODAR. Thus, the comparison with SLODAR is encouraging. It should be remembered that instruments pointed in different directions and at different zenith angles, thus measured different turbulent volumes. In these conditions, only statistical agreement is expected, but the details of the temporal variation of seeing should not match.

6 Discussion

Planet scintillometer (PlaSci) shows some promise as a tool for characterising the optical turbulence in the first kilometer. It permits to “push” the sensitivity of MASS to lower altitudes, 100 m or even below. A comparison with other instruments shows some systematic effects, not yet fully understood, and at the same time demonstrates the internal consistency and repeatability of the PlaSci results. The pros and cons of this technique are summarized below.

Pros: The method is as simple and inexpensive as MASS. Existing MASS hardware can be used, only data reduction needs to be modified.

Cons: The altitude resolution remains low, about 1/2 of altitude. At best, PlaSci can add another 2 layers below the “standard” 0.5-km MASS zone and improve the reliability of turbulence measurement in the 0.5-km zone compared to MASS.

The lack of sensitivity to the lowest and most intensive turbulence near ground restricts the usefulness of the PlaSci method. For example, it will be difficult to apply this technique to modeling vertical turbulence profiles in the first few hundred meters above ground because the first and most important point at zero altitude is missing. Moreover, the vertical resolution and sensitivity zone of PlaSci depend on the angular size and altitude of a planet, hence change with time.

The visibility of suitable planets is yet another restriction to PlaSci. Continuous turbulence monitoring is not possible, the time coverage will be variable depending on the site location and observing period.

Conclusion: It is likely that PlaSci will find only limited use as a complement to MASS and DIMM.