A New Method for Comparing Numerical Simulations with Spectroscopic Observations of the Solar Photosphere

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Abstract. A method for comparing high-resolution spectroscopic observations of the solar photosphere with numerical simulations of convection in the solar photosphere is presented. It is based on the comparison of the granular continuum contrast obtained from both the observations and the synthetic spectra, when the latter are calculated from numerical simulations using a particular type of data degradation. This method can be used post-facto when a minimum of auxiliary information on characteristics of the telescope/spectrograph and on seeing conditions is available. Here, the method is applied to results of numerical simulations computed with the CO5BOLD code and high-resolution spectroscopic observations obtained with the VTT on Tenerife.

1. Introduction

Results of numerical simulations (SIMs) and high-resolution long-slit spectroscopic observations (OBSs) of the solar photosphere still considerably differ in their typical spatial sampling since the practical spatial resolution of OBSs is spoiled by atmospheric seeing and instrumental effects. Different restoration procedures are nowadays commonly applied to allow a comparison but only a few attempts have been presented so far for the restoration of 1-D long-slit spectroscopy measurements (Keller, 1994, Keller & Johannesson, 1995, Rodríguez Hidalgo & Ruiz Cobo, 2003). The aim of our contribution is to present a forward post-facto degradation method which could be applicable to the results of numerical simulations of convection of the solar photosphere when almost no special auxiliary data on seeing conditions and telescope/spectrograph characteristics are available. This approach is different from the previously applied forward degradation procedures (e.g. Steffen & Freytag, 1991).

2. Method

For degradation of SIM data, available in form of a 3-D (x,y,λ) data cube of synthetic spectral profiles of a particular spectral line, a point spread function (PSF) is needed. Even in the simplest possible form, the PSF must contain information on both, the blurring and the scattering parts (Zwaan, 1965). Up to now several parametric forms have been applied using single or combined Gaussian and Lorentz profiles, usually derived from observations of eclipses or
planet transits. Keeping our method as simple as possible the blurring part of the PSF is deduced from its Fourier transform – the optical transfer function (OTF) – using theoretical relations derived for the case of long exposures (>1s). In this case the OTF can be factorized by a two component formula separating the atmospheric and telescopic contributions using just 3 control parameters – the Fried parameter $r_0$, the telescope aperture $D$, and the wavelength $\lambda$ (von der Lühe, 1992; Bonet, 1999). The scattering part of the PSF is in fact a rather long-tail monotonic function seen in detailed limb/aureole measurements (e.g. Deubner & Mattig, 1975). Having in mind that the typical photospheric granular size is considerably smaller than the spatial extent of available SIMs, we prefer to mimic the effect of scattering via a constant background, independent on the scattering angle over the whole spatial domain of the SIMs. Hereafter, the PSF will therefore be approximated as

$$PSF = PSF_{\text{blur}} + PSF_{\text{scatt}} = PSF_{\text{long-exp}}(D, r_0) + C \quad (1)$$

where the term $PSF_{\text{long-exp}}$ is given by the equations given in the work of Bonet (1999). Two free parameters, $r_0$ (alternatively, the radius of the seeing disk $\lambda/r_0$) and $C$, have to be determined to fully describe such an approximation to the PSF. The granular contrast of the continuum intensity, $\delta I_{\text{rms}}$, is used as a criterion to determine the appropriate values of $\lambda/r_0$ and $C$. In case of OBSs, the value of the mean granular contrast, $\delta I_{\text{rms,obs}}$, is derived from many exposures of 1-D slit spectra of the quiet photosphere. For the SIMs, the mean value of the granular contrast, $\delta I_{\text{rms,sim}}$, from several snapshots is calculated for several test PSFs with different combinations of the parameters $\lambda/r_0$ and $C$. Moreover, effects of sampling the 2-D spatial domain of the snapshots by a ‘virtual slit’ of a width equal to that used in the OBSs, detector pixel length along the slit, and estimation of the instrumental profile are introduced. Comparing $\delta I_{\text{rms,obs}}$, derived from OBSs, with the range of $\delta I_{\text{rms,sim}}$, determined for test degradation results of SIMs, the appropriate values of the parameters $\lambda/r_0$ and $C$ can be deduced. Values of $\delta I_{\text{rms,obs}}$ and $\delta I_{\text{rms,sim}}$ should coincide for such parameters. Finally, these values are used for the PSF to be applied to the SIMs in each spectral plane together with additional degradation for the slit/detector sampling.

### 3. Data

The described method has been tested using observational data described by Rybáč et al. (2004) and synthetic spectra based on the results of numerical simulations by Wedemeyer et al. (2004). Briefly, spectroscopic observations were performed using the Vacuum Tower Telescope (VTT) on Tenerife. The Fe II 6458 Å line was taken with an exposure time of 1 s, while the slit width was 0.5" and the detector pixel size along the slit 0.125". 300 spectra were acquired at center-to-limb position $\mu=0.65$ with 600 spectral rows along the slit giving an average value of the granular contrast $\delta I_{\text{rms,obs}}$ equal to 0.021. The non-magnetic 3-D numerical simulations cover a spatial domain of $7.7" \times 7.7"$ with a horizontal cell spacing of 0.055". In total, 52 snapshots with the temporal step of 3 min were calculated. The LTE radiative transfer code LINFOR3D was
Method for comparing simulations with observations

4. Application

Diverse degradations were applied to the SIMs corresponding to values of the PSF half-width of 0.14” to 1.05” and $C$ of 0.0 to $5.5 \times 10^{-5}$ (i.e. the relative ratio between the scattering and the blurring parts of the PSF of 0.0 to 0.096). For comparison, the theoretical resolution of the VTT is 0.23” at our wavelength and a scattered light level of a few percent was reported for the VTT telescope. The resulting 2-D map of the granular contrast derived from all snapshots is shown in Fig.1. It shows that for a given granular contrast the PSF half-width and the scattered light level are not uniquely determined as they slightly depend on the applied scattered light level. The granular contrast of our observations, $\delta I_{\text{rms,obs}}$, is reached within the interval of the PSF half-width from 0.60” to 0.65” (Fig.1, white curve). An estimation of the scattered light level is inevitable to solve the ambiguity. Data taken during the Mercury transit in 2003 (Soltau, 2005) were found to be the most appropriate for this purpose. Assuming that exclusively scattering is causing the rest intensity at the Mercury disk center (6 % of the nearby continuum at 5725±5 Å), a background scattered light level of just $2.2 \times 10^{-6}$ is derived for each pixel of the spatial domain of the SIMs. The corresponding ratio between the scattering and blurring parts of the PSF
5. Results

Fig. 2 shows an example of an original and a degraded SIM spectrum. Besides a decrease of the intensity range from [0.3,1.4] to [0.4,1.1], a remarkable degradation of the spectral profiles is found. For example, the range of the line-of-sight velocities, derived from the Doppler shifts, changes from ±5 km/s to only ±1 km/s. Almost all (99.6%) of our observed Doppler shifts are within the latter velocity interval.

The effects of the degradation procedure on distributions of two spectral line characteristics – the continuum intensity and the full-width at half minimum of the line (FWHM) – are shown in Fig.3, where histograms of these quantities are displayed. They have been calculated for the position \( \mu = 0.65 \) taking each snapshot individually. The histograms of the continuum intensity of the original SIM data show a wide range of values with an almost flat central part in the interval 0.8 to 1.2. The degradation procedure significantly narrows these distributions to the interval [0.9,1.1] but the significant part of the data are within the interval [0.94,1.06]. Generally, individual distributions keep their significant statistical differences also after degradation.

The distribution of the line width of the original SIM data is very asymmetric. Therefore, the most frequent value of this quantity is shifted by 10%
Figure 3. Distributions of the continuum intensity (left column) and the line width (right column) for all individual snapshots from the original simulation data (top row) and for the same data degraded for all effects including the PSF, the slit width, detector pixel sampling, and the estimated instrumental profile of the VTT echelle spectrograph (bottom row).

from the mean value. Again, the degradation is removing the far wings of the distributions below 0.8 and above 1.4. The distributions are still asymmetric and significant variations between individual distributions are present.

A comparison of the average distributions of the normalized FWHM coming from OBSs and from degraded SIMs for μ=0.65 is given in Fig.4. Both distributions show similar asymmetry but the distribution from the SIMs is broader. The difference is more pronounced for the tail of large values (~20%). For checking purposes, we have calculated a similar distribution for the continuum intensity (Fig.4). It advises that the PSF might be still a bit underestimated as the distribution of the SIMs is still broader than that of the OBSs. These preliminary results demonstrate the possible usage of this method for statistical comparison of high-resolution spectroscopic observations with synthetic data obtained from numerical simulations.
Figure 4. Average distributions of the continuum intensity (left panel) and the full-width at half minimum (right panel) for the degraded simulation data (thin line) and for the observational data (thick line) for a a heliocentric angle of $\mu=0.65$. Distributions are normalized to the mean value of the particular spectral characteristic.

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