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The solar continuum intensity distribution

Settling the conflict between observations and simulations

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Abstract. For many years, there seemed to be significant differences between the continuum intensity distributions derived from observations and simulations of the solar photosphere. In order to settle the discussion on these apparent discrepancies, we present a detailed comparison between simulations and seeing-free observations that takes into account the crucial influence of instrumental image degradation. We use a set of images of quiet Sun granulation taken in the blue, green and red continuum bands of the Broadband Filter Imager of the Solar Optical Telescope (SOT) onboard Hinode. The images are deconvolved with Point Spread Functions (PSF) that account for non-ideal contributions due to instrumental stray-light and imperfections. In addition, synthetic intensity images are degraded with the corresponding PSFs. The results are compared with respect to spatial power spectra, intensity histograms, and the centre-to-limb variation of the intensity contrast. The observational findings are well matched with corresponding synthetic observables from three-dimensional radiation (magneto-)hydrodynamic simulations. We conclude that the intensity contrast of the solar continuum intensity is higher than usually derived from ground-based observations and is well reproduced by modern numerical simulations. Properly accounting for image degradation effects is of crucial importance for comparisons between observations and numerical models. It finally settles the traditionally perceived conflict between observations and simulations.

Key words. Sun: photosphere; Radiative transfer

1. Introduction

The contrast of the continuum intensity originating from the low solar photosphere represents one of many diagnostic tests that are needed to check the realism of numerical models of the solar atmosphere (see, e.g., Deubner & Mattig 1975). In the past, there seemed to be a disturbing discrepancy in granulation contrast measurements derived from observations of the quiet Sun and from three-dimensional numerical models (see, e.g., Nordlund 1984). The historic evolution of the contrast measurements is illustrated in Fig. 1 by Kiselman (2008) for a continuum wavelength of 500 nm. Simulations produce values between 18 % and 27 %, whereas uncorrected

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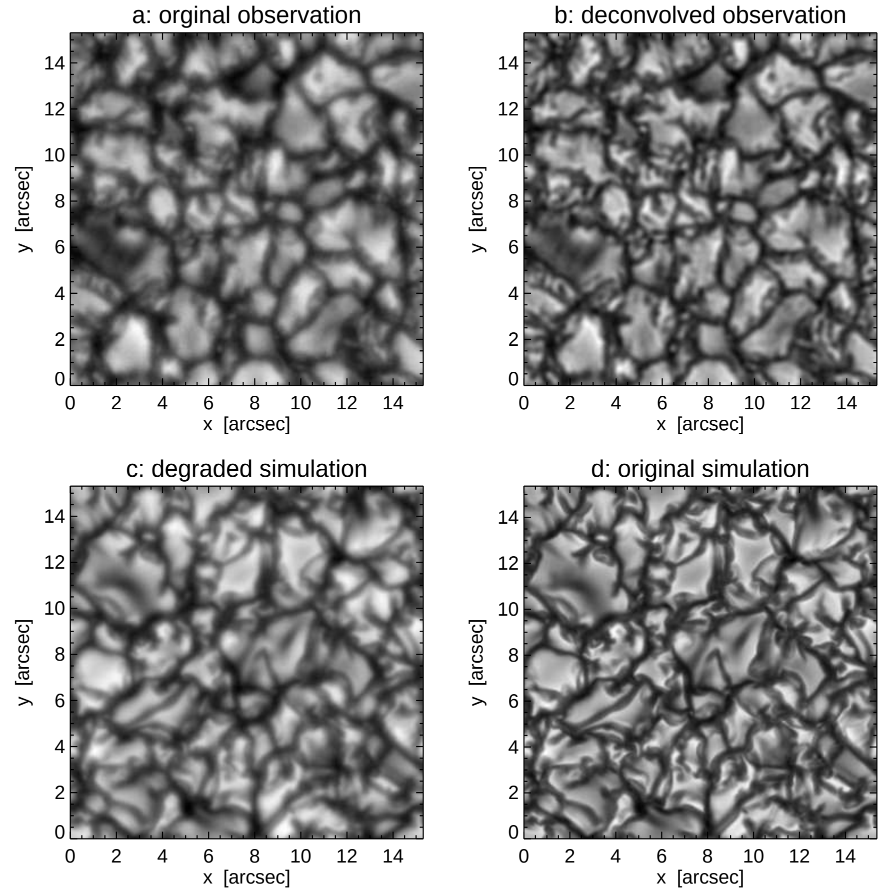

Fig. 1. Comparison of exemplary intensity maps: **a)** original observation (close-up), **b)** deconvolved observation, **c)** degraded simulation, **d)** original simulation.

observations have contrasts of only a few percent points. See also, e.g., Spruit et al. (1990) and Sánchez Cuberes et al. (2000).

This apparent discrepancy is now proven to be caused by the problematic correction of the observed intensity images. Observations have to be corrected for degradation due to instrumental effects and – in case of ground-based observations – the terrestrial atmosphere (“seeing”). Unfortunately, the properties of the degradation are difficult to be determined and therefore often only poorly known. The result is an often incomplete correction and a correspondingly too low empirical granulation contrast.

This short article summarises some of the main points from a recent more extensive study that we published in Wedemeyer-Böhm & Rouppe van der Voort (2009). By using space-borne observations with the Solar Optical Telescope (SOT, Tsuneta et al. 2008; Ichimoto et al. 2008; Suematsu et al. 2008; Shimizu et al. 2008) onboard the Hinode spacecraft (Kosugi et al. 2007), only the instrumental degradation had to be corrected for, which enabled a meaningful comparison of observations and state-of-the-art numerical simulations of the solar photosphere.

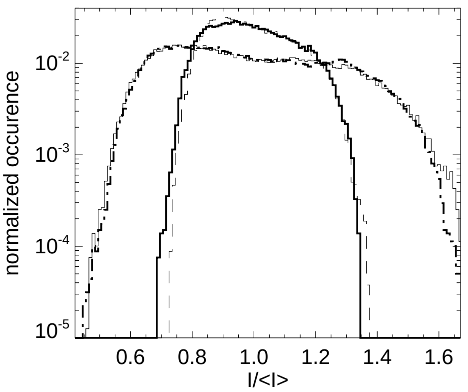

Fig. 2. Intensity distribution of the exemplary intensity images: original observation (thin dashed), deconvolved observation (thin solid), degraded simulation (thick solid), original simulation (thick dot-dashed).

2. Observations

We selected 584 images taken with the Broadband Filter Imager (BFI) of the Solar Optical Telescope (SOT). The blue (450 nm), green (555 nm), and red (668 nm) wavelength bands have been considered. Only quiet Sun regions at positions from disc-centre to the limb were chosen.

SOT has a spatial resolution of ∼ 0.″2 − 0.″3, which is clearly sufficient to resolve the solar granulation pattern. In a precursory study, statistically representative point spread functions (PSFs) were constructed for each of the channels considered here (Wedemeyer-Böhm 2008). For those, a total of 70 images of eclipse and Mercury transit observations were employed. The PSFs included the effect of the SOT aperture and an approximation for non-ideal stray-light contributions.

3. Synthetic intensity

Most of our analysis was based on three snapshots taken from a recent 3D radiation hydrodynamic simulation, which was carried out by Steffen (2007) with CO^{5}BOLD (Freytag et al. 2008). For comparison, additional simulations by Schaffenberger et al. (2006), Wedemeyer et al. (2004), and Stein & Nordlund (1998) were used. The individual models differ in horizontal grid spacing and extent, the frequency-dependence of radiative transfer, and the inclusion of magnetic fields.

The intensity synthesis code Linfor3D (see http://www.aip.de/~mst/linfor3D_main.html) was used to calculate synthetic continuum intensity maps for each wavelength band and all simulation snapshots for heliocentric positions from disc-centre to limb with an increment of $\Delta\mu = 0.05$.

4. Comparison of observed and synthetic images

We now compare exemplary intensity maps for the blue channel. Next a close-up from the original filtergram, we show the corrected intensity image in Fig. 1. The image degradation due to the instrument was corrected for by deconvolution with the detailed PSF. In this example, the granulation contrast increases from 12.4 % to 25.4 %. This compares to 25.0 % for the original simulation snapshot. Degrading the latter by applying the PSF decreases the synthetic contrast to 12.9 %. A more detailed mean of comparison are the intensity histograms displayed in Fig. 2. The original simulation has a much broader distribution than the original observation and exhibits two distinct peaks at darker and brighter than average intensity values, which is not discernible from the narrow observed distribution. Correcting for the influence of instrumental image degradation, however, produces a close match of observed and synthetic intensity distribution.

5. Conclusions

We conclude that the traditionally perceived conflict between observations and simulations in terms of granulation contrast can be dismissed. Modern simulations are obviously sufficiently realistic to reproduce the main characteristics of the (lower) solar photosphere in quiet Sun regions. It is however important to note that both sides have small but noticeable intrinsic variations, e.g., caused by selection of the field of view. One can therefore not expect an exact match of the contrast numbers.

The granulation contrast as a single number is a poor test of the realism of simulations. Evaluating a complex phenomenon like the solar surface convection requires more substantial tests. In this respect it is essential to note that also the centre-to-limb variation of the contrast and the power spectral density of the continuum intensity from observations and simulations are in good agreement.

Detailed PSFs with reliable estimates of the stray-light contributions are crucial for quantitative comparisons as shown here. Ideally one would measure the PSF exactly simultaneous to recording an intensity image. As this is essentially not possible, a robust correction for the influence of image degradation requires significant statistics employing a large number of intensity images as done by Wedemeyer-Böhm (2008) and Wedemeyer-Böhm & Rouppe van der Voort (2009). Studies using PSFs and intensity maps based on a single or a few images only are potentially misleading.

The next step towards realistic models concerns the refinement of the thermal structure and velocity field above the lower photosphere. An obvious way to test it are detailed comparisons of spectral lines as they are currently employed in the context of abundance determinations (see, e.g., Asplund et al. 2000; Caffau et al. 2008).

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