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Restoring full-disk images for atmospheric and instrumental degradation effects

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Abstract. A numerical technique developed to recover atmospheric and instrumental degradation effects on full-disk images of the solar atmosphere acquired with a medium resolution will be presented. This technique, based on the method proposed by Walton and Preminger (1999), allows simultaneous determination of the undisturbed solar limb darkening profile and the characterization of the Point Spread Function in terms of a small number of analytic parameters. The application of the technique allows to remove stray light effects from images, to a great extent, while preserves the data photometry. The results obtained applying this technique to a sample of full-disk images taken with the PSPT telescopes will be summarized.

Key words. Techniques: Image processing – Sun: Fundamental parameters

1. Introduction

Ground-based images of the Sun are, in general, degraded by "stray light". This term refers to scattering and blurring by both the Earth's atmosphere and the telescope itself. Detailed studies of solar features such as sunspots, faculae and the network necessary to model solar irradiance variations, as well as measurements of the solar image geometry, require correction for the stray light. In the following we present a technique developed to remove stray light effects to the greatest extent possible from the full-disk images obtained with the Rome-PSPT.
The technique is founded on a Fourier transform-based image restoring algorithm early proposed by Toner and Jefferies (1993) and Toner, Jefferies and Duvall (1997), then modified especially for what concerns the PSF description procedures by Walton and Preminger (1999). With respect to the one presented by the latter authors, our technique differs in the PSF fitting performed in the frequency domain, rather than in the real space.
We investigated the effects of applying the technique on the photometry of the real data acquired by applying it first to simulated images of the solar photosphere. The

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application of the developed technique results in good recovery of the underlying image geometry and photometry. We then evaluated the mean results obtained restoring real full-disk solar images obtained with the two PSPT telescopes operative at the Rome and the M. Loa sites.

2. Assumptions and data description

The image formation process at a certain time t, under the hypothesis of isoplanatism, is described in the frequency domain as follows:

$$I(u,v) = I_0(u,v) \cdot S(u,v) + N(u,v)$$

where I is the Fourier transform of collected image, $I_0(x,y)$ is the Fourier transform of the ideal not aberrated image, $S(u,v)$ is the OTF that describes both atmospheric and instrumental degradation, N is the noise and (u,v) are spatial frequencies.

The aim of the algorithm is to find a proper description for the OTF in order to deconvolve the collected image with a restaurative non parametric Optimum filter (Brault and White, 1971):

$$W(u,v) = \frac{|S(u,v)|^2}{|S(u,v)|^2 + |N(u,v)|^2}$$

The technique has been developed for application to 1kx1k images extracted from the archive of the daily observations carried out with the PSPT at the Rome Observatory (Ermolli et al. 1997, Centrone et al. 2001). These images correspond to the observations acquired each day at the three band-pass centered at CaIIK (393.3±0.25nm), Blue continuum (409.2±0.25nm) and Red continuum (607.1±0.5nm). PSPT images are obtained by a summation of many short exposure frames (30 msec) for a total integration time of about 1 second, that is much more than a typical atmospheric correlation time (10-20 msec). Moreover instrumental PSPT aberrations are estimated to be less than 1" so that we can assume isoplanatism and a radially symmetric PSF (Walton and Preminger, 1999); the latter is modeled as the sum of three gaussians, that take into account of the atmospheric and instrumental blurring, and a lorentian, that describes the atmospheric and instrumental scattered light:

$$s(r) = C_1\,[Y] + Z$$

$$Y = C_2 e^{-(\frac{r}{b_1})^2} + C_3 e^{-(\frac{r}{b_2})^2} + C_4 e^{-(\frac{r}{b_3})^2}$$

$$C_1 = (1 - a_l); \quad C_2 = (1 - a_2)(1 - a_3)$$

$$C_3 = a_2(1 - a_3); \quad C_4 = a_3$$

$$Z = \frac{a_l}{A(r^2 + b_l^2)}$$

where r is the radial coordinate (distance from the center of the sun) and A is a normalization parameter. The PSF is so described by a proper choice of the set of coefficients $\alpha = (al, a2, a3, bl, b1, b2, b3)$.

The not aberrated center to limb intensity variation (CLV) can be modeled using 5th order polynomial expansions like proposed by Pierce and Slaughter (1977):

$$i(\lambda, r) = \Sigma_{n=0}^{n=N} a_n(\lambda) \mu^n(r)$$

where μ is the heliocentric angle and a_n are functions of the wavelength λ and are tabulated.

The experimental CLV $o(r)$ will then be described, for a fixed wavelength, as $o(r) = i(r) * s(r) + n(x,y)$.

This vector is derived by data interpolating on a 0.5 px regular grid, the vector which entries are the median value of constant area annuli centered at the solar disk center. This technique allows to reduce the asymmetries introduced by solar structures and also to increase the SNR, so that we can neglect the noise in the $o(r)$ expression.

The set of coefficients that describes the PSF is derived by a least square fit:

$$\chi^2 = \Sigma_i \frac{|O(u_i) - I(u_i) \cdot S(U_i)|^2}{\sigma_i^2}$$

Fig. 1. Comparison of original and restored images. Sub-arrays including an active region observed around the disk center on September 4, 2001 at the CaII K band.

where capital letters are Hankel transforms of corresponding quantities, σ_i are standard deviations and u is the spatial frequency. The Hankel transform of the CLV function and of the PSF can be analytically derived so that just the transform O is numerically calculated. The minimization is performed by an iterative procedure that aims to find at each step an increment $\delta\alpha$ to the set of coefficients α solving the linear system

$$A \cdot \delta\alpha + b = 0$$

where $A_{ij} = \left(\frac{\partial E}{\partial \alpha_i} | \frac{\partial E}{\partial \alpha_j}\right)$, $b_i = \left(\frac{\partial E}{\partial \alpha_i} | E\right)$ and $E = O(u) - I(u) \cdot S(u)$ (Löfdhal and Scharmer, 1994). Iteration is stopped when the euclidean norm $||\delta\alpha||$ is less then an empirical threshold. The linear system is solved by Singular Value Decomposition technique (Press et al., 1989).

Once the PSF is estimated, the restoration is performed on a double size image d' defined as:

$$\begin{cases} d & \text{if } r < \gamma R \\ \alpha d + \beta m & \text{if } \gamma R < r < R \\ m & \text{if } r > R \end{cases}$$

where d is the original image, $m(x,y) = i(x,y) * s(x,y)$, R is the radius, $\gamma = 0.97$ and α and β are functions of r and satisfy the condition $[\alpha(r)]^2 + [\beta(r)]^2 = 1$. Noise is estimated on a portion of the original image far from the solar disk and subtracted by scattered light.

3. Results

We present here some results obtained applying the IDL code developed to apply the technique proposed on both simulated and real data. The PSPT images analyzed, i.e. real data, have been calibrated for the instrumental effects (i.e. dark and flat-field corrections). We analyzed a sample of 17 images obtained at the Rome site during August-September 2001 and a sample of 6 images obtained at the M. Loa site during July 2000.

Assuming the Pierce and Slaughter expansion (1977) at the PSPT Red continuum band of observation, we have generated an artificial full-disk image of the quiet Sun and added structures in order to simulate the main continuum solar features (spots, faculae and the network). We have degraded the simulated data with different realistic PSF obtaining different images that have been restored by the technique proposed. In order to evaluate the results we have considered the following quantities: the values of PSF coefficients, the rms contrast and the Power Spectrum of sub-arrays extracted from the images. We have found that a good set of coefficients is found only if the system is well initialized due to the strong oscillations of the Hankel transform of CLV.

The main results of applying the technique developed is an increase both of the image contrast and of the image content, i.e. an increase of the power spectrum density at all spatial scales (figure 1). These increases are larger on the sample of images obtained at the Rome site, than on the sample of images acquired at the M.Loa site. The former site being characterized by worse seeing observing conditions.

In particular, the rms contrast increase of solar features of real Rome images have typical values of 13% for Blue continuum images, 16% for CaII K images and 21% for Red continuum images. The Power Spectrum has an increase at typical spatial frequencies of the larger solar structures, as in figure 2. Actually, the increase

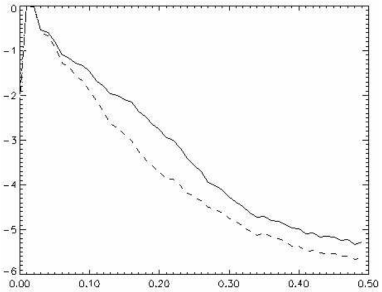

Fig. 2. Comparison of power spectral density (ordinate) at the various spatial frequencies (abscissa), being 0.5 the Nyquist frequency, computed from sub-arrays extracted by original and restored CaII K images.

is quite evident at the medium scales, while only minor changes are produced at smaller scales. This is due to a substantial undersampling of the image content and so of the PSF that limits the fitting results, really due to the scale limitation imposed by the pixel size during the image acquisition. In general, the recover of spectral density at the smaller scales is larger for the Red continuum images than both the Blue continuun and CaIIK images. Unfortunately, both the contrast and the power density increases are quite sensitive to the PSF definition.

The technique we developed is aimed to recover from PSPT full-disk images degradation effects due to atmospheric and instrumental stray-light. Up to now, PSPT data have been mainly used to quantify the contribution of magnetic regions to solar irradiance variability, as well as to study in detail temporal variations of the geometric and the photometric properties of all the magnetic structures observed on the solar disk. As a first example of the technique capability we cite the increase of correlation between measured and reconstructed signals of the solar irradiance variation (TSI) during the period spanning from 20 August- 8 September 2001 while using restored images respect to the original ones (un-restored). In this example, the reconstructed signals of the TSI were computed using photometric indexes of the magnetic features on the solar disk (Ermolli, 2001). The correlation increase between reconstructed and measured signals is about 3% using restored images.

4. Conclusions

We have presented a technique to restore full-disk images for atmospheric and instrumental degradation effects. The technique has been developed to recover these effects on the full archive of full-disk observations performed with the PSPT telescopes. This recover should allow an accurate study of long term temporal variations of both the geometric and the photometric properties of all the magnetic features on the solar disk.

We plan to modify the algorithm to perform the least square fit in the real space (Walton and Preminger, 1999) in order to increase the quality of fit results and to study seeing variations.

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