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Preliminary results on the contribution of the convection motions to the Doppler velocity signal

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Abstract. This investigation aims to study the correlation of the solar background with atmosphere. We used high resolution observations of the NaD1 spectral line. In fact the large span in formation heights of this spectral line allowed us to infer the signal from photosphere to chromosphere. We analyzed the data by applying the SIR code (Stokes Inversion based on response functions). It is an inversion method of the RTE (Radiative transfer equation) that provides physical information on the region where the spectral lines are sensitive to changes in thermal and dynamical parameters of the atmosphere. The survey has been divided in two different steps: 1) identification of a model of the atmosphere that reproduce our observations; 2) determination of the degree of correlation of convective motions with the solar atmosphere. Here we present the results of the first step: we identified in the model presented by Vernazza the best model that matches our observations.

1. Introduction
When observing solar oscillations through velocity measurements, the solar velocity fields associated with solar background (granulation, mesogranulation, supergranulation and active regions) limits the sensitivity of our measurements. Fig. 1 shows the Power spectral density of the Doppler velocity signal measured by GOLF over 1290 days of observations starting from 1996 April 11 to 1999 October 22 ([13]). We can identify several terms that contribute to the observed signal, having different origins. In the region of 1500-5000μHz, we recognize the well known structure of the 5 minute solar oscillations. At lower frequencies, 10^{-4}Hz-10^{-3}Hz, convective motions, mainly the granulation, contributes to the Doppler velocity signal; while going down, at around 10^{-4}-10^{-5}, supergranulation and active regions are the main sources. Hence low frequency modes (all modes below ≤ 2000μHz) are strongly affected by convective motions and depending on the frequency the different components of the solar background becomes much stronger then the oscillatory signal. Low frequency modes are very important in helioseismology, because are the ones that penetrate in the deeper layers of the Sun’s interior. Therefore, the need to improve our knowledge of the solar interior, requires a better signal to noise ratio at low frequency. It has been shown that the combined analysis of independent data from GOLF one wing velocity time series substantially reduce the granulation noise in the region hwere we expect to measure the low degree order p and g mode [6]. Then the idea of this survey is to study the correlation of solar background with atmosphere with NaD1 spectral.
line. During the last two decades the vertical structure of the solar photosphere has been investigated by different methods. This can be done by different techniques. One is to assume a certain model of the atmosphere and to obtain through forward modelling synthesised observable parameters which can directly be compared with observations. See the numerical simulations of solar convection by Steffen et al.[11][12], Gadun et al. ([3][4],[5]), Freytag ([2]) and Wedemeyer et al. ([15]). Another technique is to invert the observations in order to obtain the model atmosphere through iteratively comparing synthetic observable with real ones. Several inversion methods have been developed. We are going to use the Sir code developed by B.Ruiz Cobo ([1]). It fits the intensity profile coming from the user provided model of atmosphere to the one from the observations. Therefore it is able to reproduce the observed spectral line profile. Then we obtain a synthetic spectral line that matches our observations and the physical parameters that describe the atmosphere where the spectral line changes occur. Once we disentangle the oscillatory signal by the solar background, we can study the solar background with atmosphere. In this preliminary survey we show that the model of atmosphere that fits well our observations is Vernazza et al. In the forthcoming feature we will present the results about the correlation backgrounds with atmosphere.

2. The Data sets

2.1. The observations

Thémus telescope allowed to make high resolution measurements of NaD1=5896Å. We choose this line because of the large span in formation height ([7]). The observations have been taken on the 30th of August 2005 in the quiet and active Sun. They consist of time series of about 50 minutes of high resolution with a cadence time of 50 seconds. The spatial resolution is 0.44 arcsec per pixel.
2.2. The absorption line profile

Fig. 2 shows the observed line profiles compared to the one gathered from the instruments placed aboard three space platforms, the ATmospheric Laboratory for Applications and Science (ATLAS). The NaD1 spectral line is disturbed by the presence of a blended Fe line at 5895.007 and with two unknow lines at at ~ 5896.3. Further we can distinguish other features:
- the level of the continuum is a bit different from the one provided by the ATLAS spectra;
- the bottom of the line is a bit higher up compared to the one provided by ATLAS
- the position of the minimum is shifted towards blue value.

We adjusted these differences by performing the calibration of the signal with the one provided by the ATLAS spectra.

3. The technique and results

3.1. The SIR code

SIR is a package for the synthesis and inversions of spectral lines formed in the absence or presence of magnetic fields ([1],[8],[9]). It starts from a model of the solar atmosphere and then by solving the radiative transport equation (RTE), it fits the intensity profile coming from the model to the one from the observations. We, therefore, are able to reproduce at every moment the observed line profile and to determine physical parameters such as temperature, pressure, density, vertical velocity flow that characterizes the environment in which the changes of the line profile take place. We identified in the model of Vernazza the one that matches our observations. In the forthcoming feature then we are going to study the features of the convective motions at different altitudes in order to determine the degree of correlation with atmosphere. The code takes into account the Zeeman induced polarization of the light and deals with all four Stokes parameters (I,Q,U,V) of any electron dipole transition and atomic species. It can work under two different regimes:
- *Synthesis mode*

In synthesis mode the program calculates the Stokes spectra emerging from any specified model of atmosphere. This has been done by solving numerically the radiative transfer equation (RTE)

\[
\frac{dI(\tau_5)}{d\tau_5} = K(\tau_5)[I\tau_5 - S\tau_5]
\]

where \(\tau_5\) represents the continuum at the optical depth of 5000A, \(K\) is the total absorption matrix describing the absorption properties of the atmosphere and \(S\) is the source function vector \(S=(S_1,S_2,S_3,S_4)\). Since LTE condition are assumed, the source function is given by

![Figure 2. The observed (plus sign) and ATLAS (continuous line) NaD1 absorption line profile](image-url)
Planck’s function at the local temperature $T$. In our investigation we performed high resolution measurements in the quiet Sun, that is with a magnetic field almost zero. Hence Eq. 1 becomes:

$$\frac{dI(\tau_5)}{d\tau_5} = K(\tau_5)[I(\tau_5) - S(\tau_5)]$$  \hspace{1cm} (2)

and $K$ is a coefficient and $S$ is the source function. - **Inversion mode**

In inversion mode, SIR fits any combination of observed line profiles for any arbitrary number of spectral lines. To this end, an initial user provided model atmosphere is iteratively modified until the synthetic Stokes profiles match the observed ones. This process yields the thermal, dynamic and magnetic structure of the atmosphere in which the observed profiles were formed. The inversion code proceeds by minimizing a merit function which is the sum of the squared differences between observed and synthetic data weighted by the uncertainties of the observations and by some factors. The merit function is defined as

$$\chi^2 = \frac{1}{\nu} \sum_{k=1}^{4} \left( \sum_{i} \frac{[I_{k,\text{obs}}(\lambda_i) - I_k(\lambda_i)]^2}{\sigma_{ki}^2} \right)$$  \hspace{1cm} (3)

At the end of the procedures, we get two different datasets:
1) spectral line determined by the inversions that can be compared with the observations;
2) vertical velocity flow, temperature, optical depth, density, electronic pressure related to one particular spectral line. This allows us to derive the photospheric thermodynamic and dynamical properties needed to reproduce the observed spectral line at every moment.

### 3.2. The observed and inverted spectral line profile

The model of the atmosphere used to carry out the inversions is described in Vernazza, Avrett, Loeser ([14]). For our purposes we decided to apply SIR code to the high resolution time series containing the NaD1 line. The original code calculates the atomic level population under LTE approximation. Nevertheless, departures from LTE have proved to be important for this line. These departures mainly affect the line source function, which deviates significantly from Planck’s function as one proceeds outward in the atmosphere. We have already shown that the formation height of this line involves the chromosphere. We overcome this limit by taking into account fixed departure coefficients for a given model of atmosphere. Fig. 3 shows a comparison between two inverted and observed profiles. The blue/red line is the inverted profile, while the blue/red squared are the observed ones. As we can see in both cases the agreement between observations and inversions is very good. This is very important to us, because it means that we can get a good description of the layer of the atmosphere where the spectral line has been formed. Further by studying the properties of the spectral line, we have the chance to link one particular spectral line to a granule or intergranule. The granular phenomenon can be described in the following way: convective overshoot of the plasma from the solar convection zone into photosphere forms a pattern of bright cellular elements showing upward motion—the granules—surrounded by a network of dark intergranul lines, where the down-flow motions are observed.

Hence granules are much hotter than intergranules and therefore they have greater value in the intensity continuum compared to the intergranules and to the surrounding medium. Therefore we identified the spectral line formed by a granule, by selecting the spectral line whose level in the continuum was higher than 0.90; while we identified the spectral line produced by an intergranule by selecting spectral line whose level of the continuum is below 0.85. The spectral line associated to a granule/intergranule is shown in Fig. 3. As we can see the two inverted/observed line profiles are shifted. The blue one is shifted towards higher values in intensity and towards blue values in wavelength. This is the way we can identify a granule. While intergranules, that are cooler...
than granules, have low intensity and are shifted towards red regions. This procedure allowed us visualize the change induced by granulation on the spectral lines.

4. Conclusions

In this preliminary survey, we analyzed high resolution time series of NaD1 spectral line by applying the SIR code. With the inversion technique SIR, we obtained a model of the atmosphere that identify the enviroment in which the spectral line is formed. Thanks to this we have been able to reproduced the observed spectral line with a very good agreement. We used several models before finding the Vernazza et al. the one tha fits better our observations. Fig.1 shows in fact the observed and simulated spectral line and we can easily observe the good agreement. Further the model of atmosphere gives us a measure of the vertical velocity $w_{\text{ou}}$, where with this word we mean the velocity associated to solar oscillations and the one associated to the convective motion. The next step then will be to desentangle the Doppler velocity signal in two terms: one produced by solar oscilations and the other by convective motions. By doing so, we can study the degree of correlation at different altitudes in solar atmosphere of the convective motions. This is an important point in solar oscillations measurements, above all at low frequencies. As it has shown by Turck chieze et al the main source at low frequency is the convective motions. Then if we want to improve solar oscillations measurements it is of vital importance to understand the convection and to understand how to desentangle this term from our measurements.

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