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Observations of the radial velocity of the Sun as measured with the novel SONG spectrograph: results from a 1-week campaign

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Abstract. Deployment of the prototype node of the *SONG* project took place in April 2012 at Observatorio del Teide (Canary Islands). Its key instrument (echelle spectrograph) was installed and operational a few weeks later while its 1 m feeding telescope suffered a considerable delay to meet the required specifications. Using a fibre-feed, solar light could be fed to the spectrograph and we carried out a 1-week observing campaign in June 2012 to evaluate its performance for measuring precision radial velocities. In this work we present the first results of this campaign by comparing the sensitivity of the SONG spectrograph with other helioseismology reference instruments (*Mark-I* and *GOLF*) when simultaneous data are considered.

1. Introduction

The Stellar Observations Network Group (SONG) is an international initiative, led by the Stellar Astrophysics Centre (Aarhus University) and Niels Bohr Institute (University of Copenhagen), to design and build a global network of small telescopes (Grundahl et al. [5]). The goal of SONG is to become a key facility in both asteroseismology and planet-search research programs, a facility that provides state-of-the-art data of a quality that could not be achieved by use of any other space-based or ground-based facility. SONG is proposed to have a total of eight nodes in the northern and southern hemisphere. By placing the telescopes at roughly equally spaced longitudes, long-term nearly continuous observations can be obtained. Each telescope has an aperture of 1 m and will be equipped with a high-resolution spectrograph for measuring very precise stellar radial velocities and dual-colour lucky-imaging cameras for photometry of faint stars in crowded fields. The first-prototype node was completely deployed in April 2012 at Observatorio del Teide, a well-reputed observing site already hosting nodes of the major helioseismology networks (BiSON and GONG). In this work, we present the results obtained with the novel SONG spectrograph when observing a reference star, the Sun, and further to compare the achieved sensitivity to velocity fluctuations with simultaneous data obtained with specific helioseismic instruments such as Mark-I (located few hundred meters away from SONG) and GOLF (aboard the SoHO satellite).

2. Observations and data analysis

2.1. SONG spectrograph

As part of the original design, the system included a fibre feed which allows us to direct sunlight into the spectrograph (see Fig. 1). The first test results were very encouraging and we subsequently mounted the fibre on a normal-incidence pyrheliometer tracking the Sun and carried out a short campaign of a week (11 to 16 June 2012) in which we observed continuously during a 10 h period each day. The SONG echelle spectrograph is equipped with an Iodine cell for wavelength reference, covering the interval 4800 to 6700 Å and a spectral resolution up to 110000 and CCD focal plane of 2K x 2K pixels. Images were taken continuously every 2.8 s and basic reduction was performed using an ad-hoc pipeline written by one of us (FG) and still under development (Triviño et al. [9]). The spectra are extracted using the REDUCE package developed by Piskunov and Valenti [8], while the precise line-of-sight velocity determination (`iSONG` package) is based on the technique developed by Butler et al. [2]. In Fig. 2 the obtained solar radial velocity, residuals and their Power Spectrum Density (PSD) are shown.

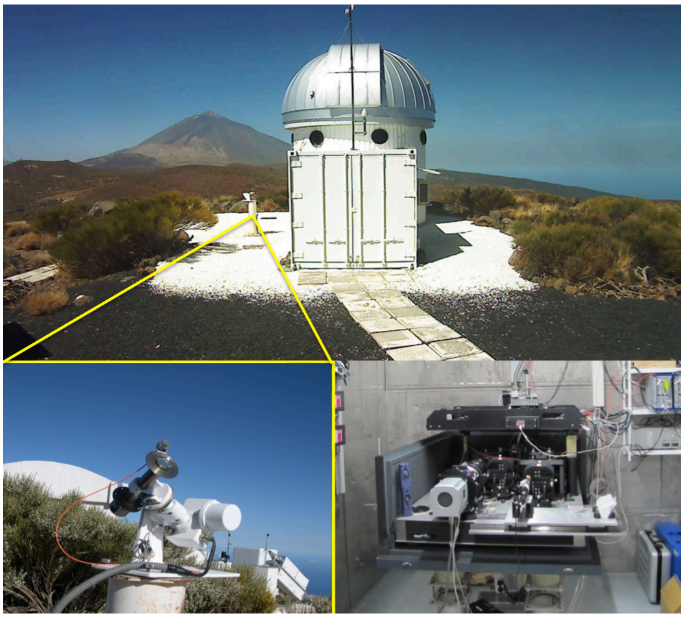

Figure 1. SONG telescopic installation at Observatorio del Teide (telescope & laboratory) and a zoom at the normal incidence pyrheliometer with the attached fibre optic to feed the SONG echelle-spectrograph (bottom right) with solar light.

2.2. Mark-I spectrophotometer

Mark-I is a sun-as-a-star resonant scattering spectrophotometer (Brookes et al. [1]) operating at the blue and red wings of the potassium KI 7699 Å line. It is a reference instrument in helioseismology and the seed node of the BiSON Network that has been continuously operated since 1976 at Observatorio del Teide. Daily data consists of a 2 s interval measurement of

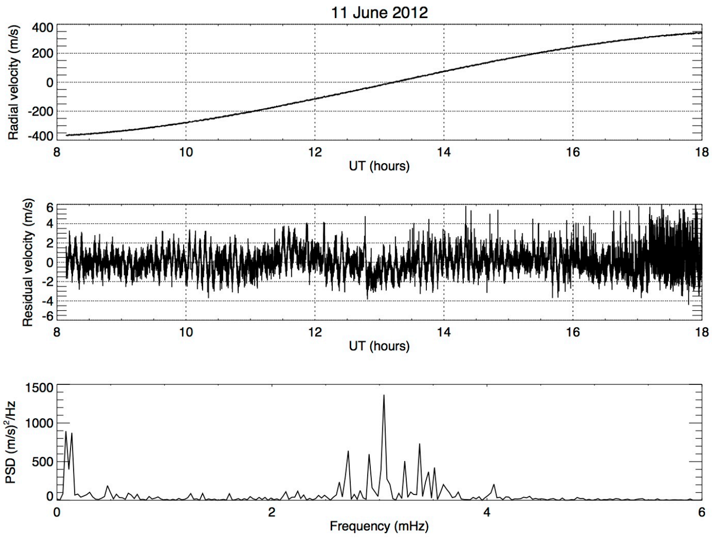

Figure 2. Reduced raw data output from a daily solar run (11 June 2012) with SONG spectrograph. The relative line-of-sight velocity (top), residuals after a polynomial fitting (center) and its PSD (bottom).

the instrumental line-of sight velocity which is further calibrated and detrended to obtain the residual velocity (see the whole procedure in Pallé et al. [7]).

2.3. GOLF/SoHO spectrophotometer

This sun-as-a-star resonant scattering spectrophotometer (Gabriel et al. [3]) provides continuous measurements (since 1996) at a single wing of the Na D1 - D2 solar spectral lines (5890 and 5895 Å). The calibrated data (García et al. [4]) consists on the solar residual velocities every 20 s in which barycentric velocity corrections were performed and low frequency trends (T > 3 days) removed. At present, the GOLF photon noise is more than 20 times higher than at the beginning of the mission.

3. Comparison between simultaneous ground-based and space observations

In order to assess and to compare the SONG spectrograph sensitivity, a well known small solar velocity feature has been chosen: the acoustic 5-min solar eigenmode signal. The characteristics of this signal as measured simultaneously by a neighboring instrument (Mark-I) and with another located in space, constitute a robust indicator of its performance. To undertake this comparison, the following procedures were applied: a) synchronization of data acquisition times; b) selection of a common sampling time for all data sets, long enough not to loose the 5-minute p-mode signal. A sampling time of 60 s was selected and averages were performed over 30 Mark-I consecutive points, 21 for SONG and 3 for GOLF. A prior filtering of high frequencies ($\nu >$ 8 mHz) was performed to avoid aliasing, with a FIR digital filter with zero-phase distortion (Oppenheim, A.V. and R.W. Schafer [6]); c) Removal of low frequencies ($\nu <$ 0. 8 mHz) to enhance and to isolate the 5-min band. The same filtering technique as in b) has been used, with a high-pass ad hoc filter design. In Fig. 3, the expanded residuals for some of the observing days and for SONG and Mark-I data, are shown.

A step further in this comparison was undertaken by computing the PSD for each daily run from 11 to 16 June, for each of the data sets and all of them having the same observational window (length). In Fig. 4 the daily averaged power spectra of the three data sets are shown.

4. Conclusions and perspectives

The stellar-designed SONG spectrograph has proved to perform extremely well, in terms of sensitivity to small velocity fluctuations and mid-term stability, along its *first-light* measurements

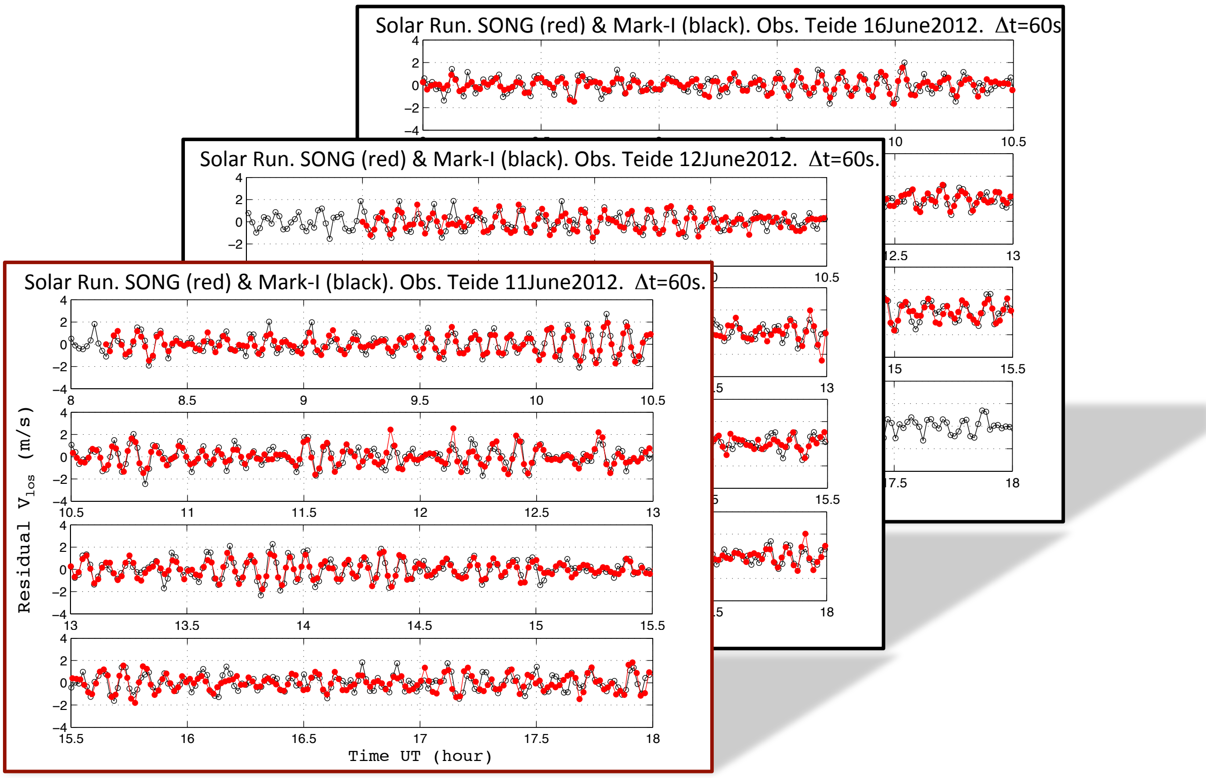

Figure 3. SONG and Mark-I residual velocity signals for different observing days of the run. Each daily signal is expanded in 2.5 hours raw to clearly distinguish the coincidence of the signals and the 5-min feature.

of a particular stellar object: the Sun. Comparative analysis with simultaneous ground and space data gathered with other instruments (Mark-I and GOLF/SoHO) has been performed and confirmed the expected performance of SONG spectrograph. A more extensive analysis based of a six days time series is currently ongoing and it will allow (although limited resolution of 2 μHz) to compare some properties of individual solar p-modes as seen with the different instruments (wavelengths). These obtained results are interesting enough to consider the possibility to perform future routine solar observations with SONG.

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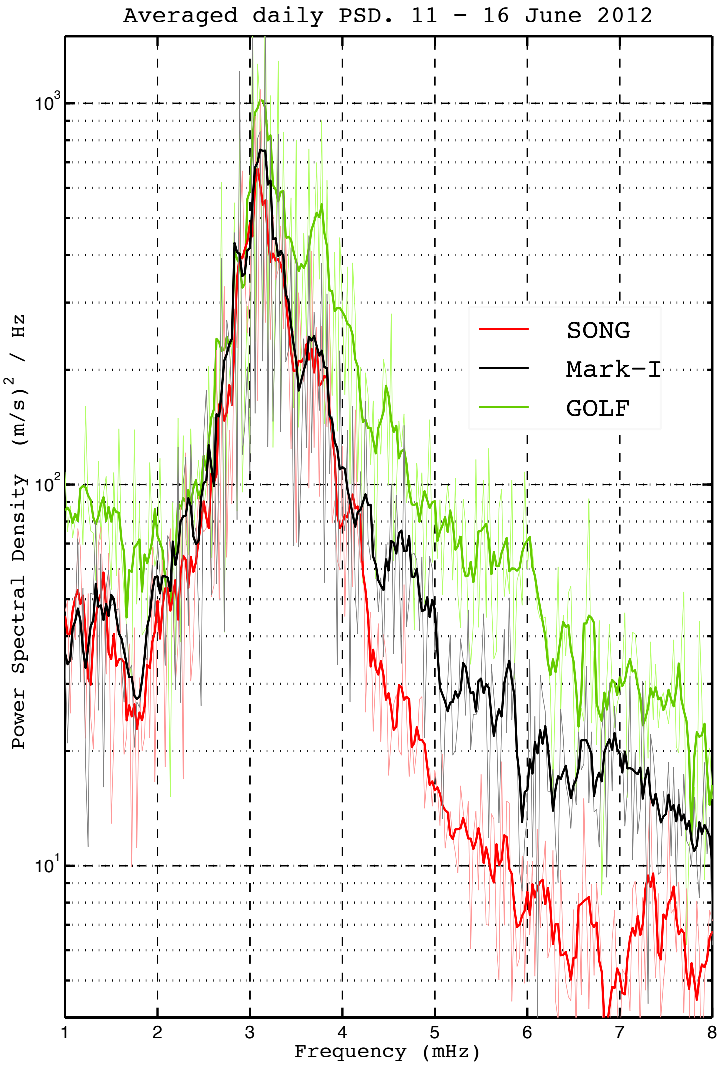

Figure 4. Average of the 6 daily power spectrum density (PSD) computed for each of the three simultaneous data sets. Thin lines correspond to the raw spectra and thick lines are the smoothed ones (5 points). The frequency resolution of the spectra is of ∼ 27 μHz. The power of the peaks around 3 mHz is slightly different for the various data sets (40 %) and most likely related with the different sensitivity to the sounded layers at the solar atmosphere. At high frequencies (dominated by photon noise), SONG data shows a 2.5 and 4.4 lower values than Mark-I and GOLF respectively.

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