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A two color pupil imaging method to detect stellar oscillations

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Abstract. Observations of stellar intensity oscillations from the ground are strongly affected by intensity fluctuations caused by the atmosphere (scintillation). However, by using a differential observational method that images the pupil of the telescope in two colors at the same time on a single CCD, we can partially compensate for this source of atmospheric noise (which is color dependant) as well as other problems, such as guiding and saturation. Moreover, by placing instruments at different locations (eg. Dome C and South Pole) we can further reduce the atmospheric noise contribution by using cross-spectral methods, such as Random Lag Singular Cross-Spectrum Analysis (RLSCA). (We also decrease the likelihood of gaps in the data string due to bad weather). The RLSCA method is well suited for extracting common oscillatory components from two or more observations, including their relative phases. We have evaluated the performance of our method using real data from SOHO. We find that our differential algorithm can recover the absolute amplitudes of the solar intensity oscillations with an efficiency of 70%. We are currently carrying out tests using a number of telescopes, including Big Bear, Mt. Wilson, Teramo and Milano, while waiting for the South Pole and Dome C sites to become available.

Key words. Asteroseismology - South Pole - Instrumentation

1. Introduction

For a general introduction to asteroseismology we refer the reader to the contribution of Donald W.Kurtz in these proceedings. The reasons why seismology of distant stars is better accomplished from space are the: 1) absence of atmospheric noise and 2) ability to observe without interruption for extended periods of time (i.e., months). However, even the approved space projects such as COROT and EDDINGTON still require ground-based support and data collection, thus providing us the motivation to develop new observing techniques. Here we propose a method for detecting stellar oscillations, especially for solar-like stars, that is based on precise photometry measurments. The two major sources of noise for this type of measurement are scintillation and image motion. By focusing the telescope pupil on the detector, as shown in our configuration below, we reduce the sensitivity to image motion noise. Thus leaving scintillation noise as the main obstacle. By selecting an observing site with close to achromatic scintillation conditions, our approach will enable us to detect signals in the temporal series of data of the order of millimagnitudes which allows us to extract signals of the micromagnitudes in the final Power Spectra.

2. The Antarctic Sites

We plan to install our asteroseismological equipment at the French-Italian Dome C and American South Pole (Amundsen-Scott) sites, both of which allow long, uninterrupted observations during the Austral winter. The observing conditions at these sites can be characterized by measurements of the temperature fluctuation constant $C_T{}^2$. Two separate groups have done this for South Pole. One using the SODAR technique (Travouillon T. et al., 2003, A&A 400, 1163-1172) and the other using balloons carrying micro-thermal sensors, both differential and absolute, along with a pressure detector (Marks R.D. et al., 1999, A&A Supplement 134, 161-172). The results of both experiments were generally in agreement and show the turbulence is, on average, concentrated inside a boundary layer sitting below ≈250 meters. As for the Dome C site, several contributions at this meeting suggest that it may have significantly lower atmospheric noise than South Pole and thus be a better site for astronomical observations. To characterize the seeing conditions using $C_T{}^2$ data, we turn to the theory of seeing as presented by F. Roddier (1981, Progr Opt. XIX, 281). Here scintillation noise results from an integral involving $C_T{}^2$ over the heights; in particular, its chromaticity depends on the way $C_T{}^2$ behaves above the telescope. In our case, starting from the general expression for the relative intensity variance, we conclude that if the boundary layer is confined below 250 meters, then the scintillation noise can be treated as achromatic if we use a 40 cm telescope. Larger telescopes would of course perform better, but smaller telescopes would produce chromatic scintillations. The articles by Travouillon et al. and Marks et al. do not consider the free atmosphere in the same way. The former ignores its contribution, while the latter quotes a contribution of 20% to the seeing, but only 7% to the integrated optical turbulence. As far as its chromatism, it needs further attention and verification. In using our two site strategy and the software described in the data analysis paragraph, we no longer consider chromatism as a problem.

3. The optical design of our asteroseismic detector

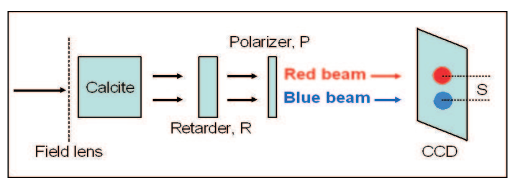

Fig. 1. Two color pupil image - Optical scheme.

We are now able to appreciate the strategy of our Two Color Pupil Imager, as proposed during the last IRIS meeting in Uzbekistan (Cacciani, A.). Our system works by making the scintillation noise as achromatic as possible since the stellar pulsations are chromatic: their amplitudes are larger in the red band compared with the blue one. We have verified this occurrence with solar data taken from SPM on SOHO and found that the signal is better

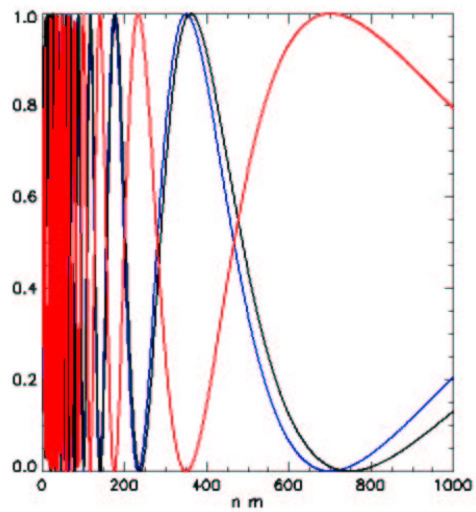

Fig. 2. Theoretical transmission curves of the Two Color Imager. The double curve of the blue band show the amount of displacement for a polarizer rotation of 0.1 rad, for calibration purpose.

than 70% (Richard Wachter of the Swiss group of C.Frohlich, private communication). Comparing the red channel (5 nm near 862 nm) and the blue (5 nm near 402 nm) and (red - blue), the decrease in signal to noise ratio for the most prominent peaks was from 15% to 30% (red - blue compared to red). This result suggests that we can adopt a differential method to eliminate the scintillation noise during the data acquisition. Fig. 1 shows the optical layout of our photometer. The advantages are: no image motion on the CCD, uniform intensity distribution inside each pupil image at the maximum size allowed by the CCD (so that no saturation occurs for longer integration times), no critical pointing needed for the star, simple and robust optical design, possibility of introducing known fractional variation of the relative difference between the two colors on the same chip. The working principle is similar to the Faraday rotation: the retarder R acts differently for different incoming polarizations and wavelengths; the polarizer P transmits as shown in Fig. 2, different R determining the wavelength position of the transmission curves; the curves of this figure can be displaced by rotating P and they are interchanged when P is rotated by 90 degrees; provided the rotation angle is accurately measured, this method can be used to introduce a known fractional signal for calibration; the shape of the transmission curves at lower and higher wavelengths are ineffective because of the stellar spectrum and CCDs sensitivity limits. There are obvious optical constraints to fullfill to avoid overimposition of the two pupil images and to fit their sizes on the detector: this depends on the telescope and CCD format. Instead of a calcite splitter we could use a Wallaston prism as well: the optical constraints will be more easily fullfilled.

4. Our first test and target selection

We have tested the two color pupil method at the Teramo Observatory. In that occasion we have selected a target fairly bright with large amplitude in the frequency range acceptable for our limited run of 5 hours. It was HD194093 (gamma-Cygni) that was observed for two nights resulting in consistent Power Spectra shown in Fig. 3. Peaks are visible in the range between 0.5 and 1.5 mHz, as the theory predicts.

5. Data analysis

A suitable selection of data reduction techniques is important in order to minimize any additional numerical noise (see for ex. Kjeldsen & Frandsen, 1992). In our case we also take advantage of the availability of two sites, South Pole and Dome C, crosscorrelating simultaneous observations from them. Moreover we will make use of the Singular Spectrum Analysis (SSA; Ghil et al., 2002). This paragraph is intended to briefly describe this method since it is a powerful tool to recover small signals from overwhelming noise. The Singular Spectrum Analysis was originally developed to search for oscillations in short and

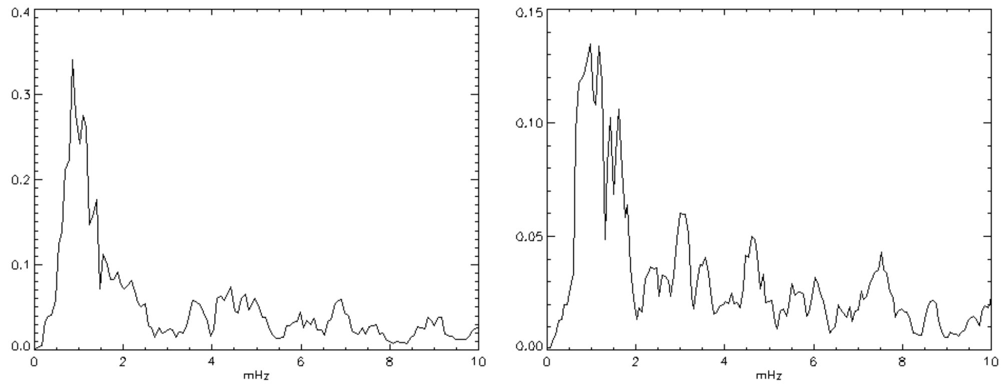

Fig. 3. Power Spectra of HD194093 (gamma-Cygni), obtained in two different nights.

noisy time series in geophysics. The technique works with the eigenvalues and eigenvectors of autocorrelation matrices. Large eigenvalues correspond to signal, small ones to noise. Signal is extracted from the time series using filters which are derived from the eigenvectors of large eigenvalues. In the original version of SSA, the sizes of the autocorrelations matrices are usually a third of the length of the time series which limits the feasibility of the method to time series no longer than a few thousand. Random-Lag Singular Spectrum Analysis (RLSSA; Varadi et al., 1999) is a generalization of SSA which can be used on long time series. It works with autocorrelations at random lags up to a maximum lag comparable to the length of the time series. Random-Lag Singular Cross-Spectrum Analysis (RLSCSA; Varadi et al., 2000) is a generalization of RLSSA to search for common oscillations in two or more time series. RSCLSA has been used to identify low angular degree solar modes of very small amplitudes (Bertello et al., 2000), which was not possible by other means. Most of the early identifications have already been confirmed with other techniques, but based on additional data. RLSCSA essentially provides a decomposition of the signal which is different from that of traditional Fourier transform-based techniques. The actual computations boil down to the following. First, if it is necessary, the data are pre-whitened by computing and applying a filter which does not alter phases. In asteroseismology, prewhitening is not likely to be required. Next, cross-correlations between the given time series are computed, for all possible lags. Then a square matrix is formed whose elements are random samples of the cross-correlations, with random lags. The singular values and vectors of the matrix are computed by standard means and only the singular vectors with the largest singular values are kept. The rest of the singular vectors presumably correspond to noise and dropping them achieves the separation of signal from noise. Next, finite impulse response (FIR) filters are created from the singular vectors that correspond to signal. These filters provide the spectral information contained in the retained singular vectors, i.e., their Fourier transforms have peaks at the frequencies that one should consider as possible mode candidates. In the case of two or more time series with known time lags, the relative phase information contained in the filters can also be used to further separate signal from noise. RLSCSA can also handle missing data, to a large certain extent. In essence, the covariance estimates used need to be rescaled according to the number of data point pairs which contribute to a given covariance value. This is a straightforward procedure which has been discussed by Scargle (1989) but in the case of RLSCSA fast Fourier transforms are used to compute the scaling factors. However, when there is no data to provide any estimate of covariance for a given lag, one has to be content with using zero for the covariance. This happens, of course, in the case of nightly single-site asteroseismology since observations at night cannot be correlated with those during the day.

6. Summary and conclusions

We have described an observational and data reduction strategy that will minimize noise in asteroseismic observations from the ground. Our two color pupil imaging system is designed to remove scintillation noise. The compensation can be partial or complete, depending on the chromatic behavior of the noise. The Antarctic sites, with turbulence confined below 250 meters, and moderate sized telescopes (≈0.5 m) would be our ideal choice. A larger telescope would assure complete achromaticity of the scintillation fluctuation, and by using a two color measurement it will be completely removed.

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