Helioseismology with PICARD

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Introduction

PICARD is a CNES micro-satellite launched in June 2010 (Thuillier et al. 2006). Its main goal is to measure the solar shape, total and spectral irradiance during the ascending phase of the cycle. The SODISM telescope onboard PICARD allows us also to conduct a program for helioseismology in intensity at 535.7 nm (Corbard et al. 2008). One minute cadence low resolution full images are available for a "medium-ℓ" program and high resolution images of the limb every 2 minutes allow us to study mode amplification near the limb in the perspective of g-mode search. First analyses and results from these two programs are presented.

Medium- l program in intensity

Full continuum images at 535.7 nm (bandwidth 0.5 nm) are recorded by SODISM every minute with a spatial resolution of about 1 square arcsecond on a 2048^2 CCD. For telemetry reasons, these images are downgraded to 256^2 pixels (about 8x8 arcsecond) by a simple onboard binning before being transmitted to ground. We have analyzed a dataset covering 209 consecutive days (2011/04/16-2011/11/10) with a duty cycle of 74.4%. The gaps are mostly due to interruptions for the other PICARD program (astrometric measurements at different wavelengths) and to the crossing of the South Atlantic Anomaly which strongly impacts the photometric signal.

Figure1 (top) shows the ℓ-ν diagram obtained from this 209-day dataset for degree up to ℓ=300. As expected we see spatial aliasing for spherical harmonics above ℓ=200. We also see temporal aliasing for frequencies above 4.5 mHz. This is the signature of a spurious cycle in the 2 mn sampling slots corresponding to the astrometric program sequences.

Figure1 (bottom) illustrates an m-ν diagram for ℓ=100 clearly showing the S-shape signature of the differential rotation rate.

Figure 2 shows mode parameters modeled using asymmetric Lorentzian profiles and fitted using a Maximum Likelihood Estimator minimization (Appourchaux et al. 1998a, Jimenez-Reyes 2001). Positive asymmetries are found which are consistent with previous analyses of intensity signal. The a_3 splitting coefficients plotted as a function of the mode turning point proxy ν/L exhibit also a gradient which is a typical signature of the solar tachocline.

Figure 3 shows the RLS inversion of the measured rotational splittings of 456 modes from ℓ=10 to ℓ=115. For a given mode (n,ℓ), each m-spectrum were individually fitted. An expansion on orthogonal polynomials (Schou, 1992) with up to 9 coefficients was then determined on the m-frequencies which passed some quality criteria. The steep gradient of the tachocline at the base of the convection zone is clearly seen in our data . The inferred rotation rate in the convection zone is similar to the one usually obtained from velocity data.

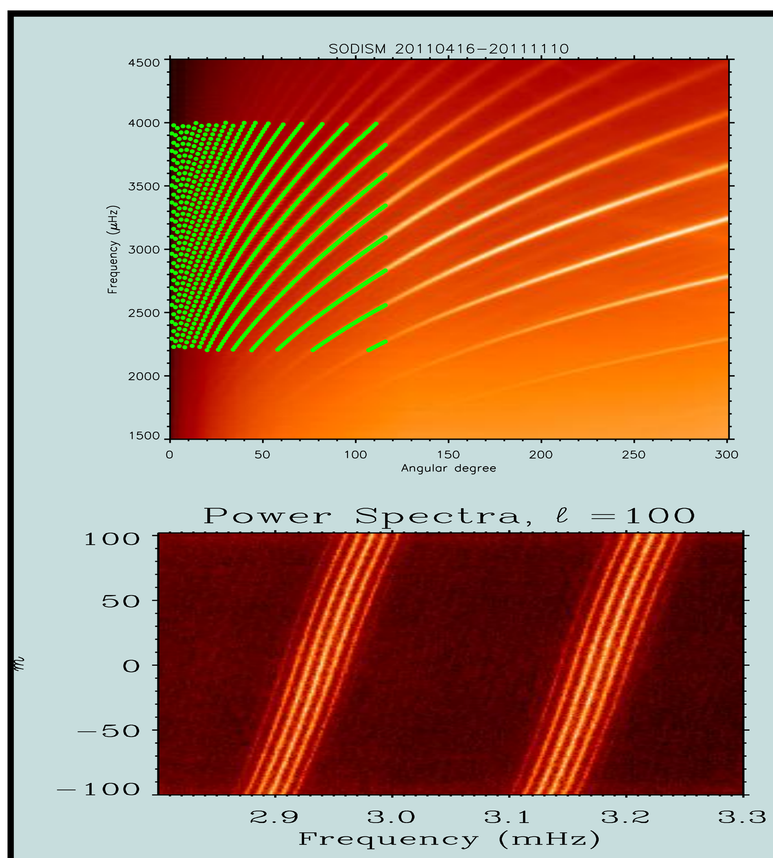

Fig 1: *Top:* ℓ-ν diagram from 209-day observations. The fitted modes are shown by the green dots. *Bottom:* m-ν diagram for ℓ=100 and radial order n=6 (left) and n=7 (right). The ℓ-leaks from ℓ=100±3 are clearly seen.

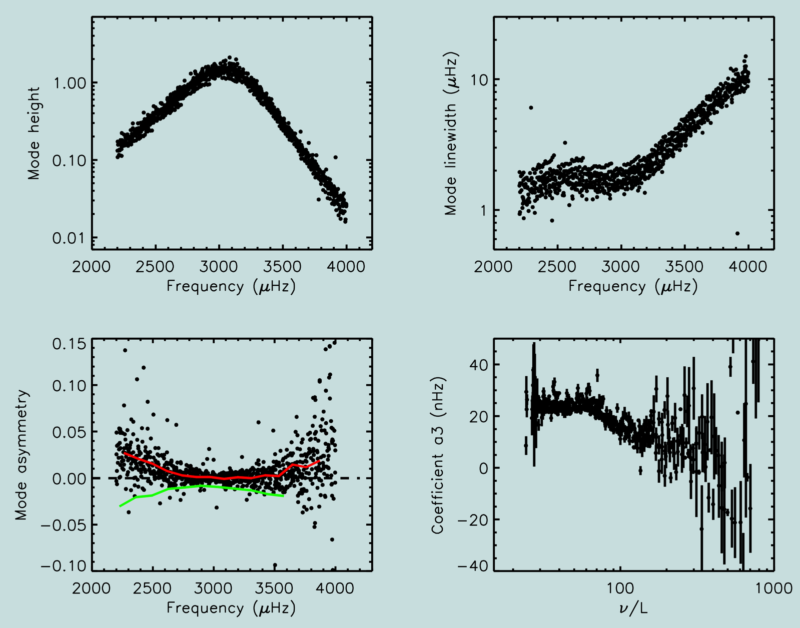

Fig 2: Fitted mode parameters: Amplitude (upper left) ,linewidth (upper right), peak asymmetry (lower left) and a_3 splitting coefficients (lower right). The red line is a fit of SODISM positive asymmetries in intensity while the green line shows the negative asymmetries obtained from SOHO/GOLF velocity signal.

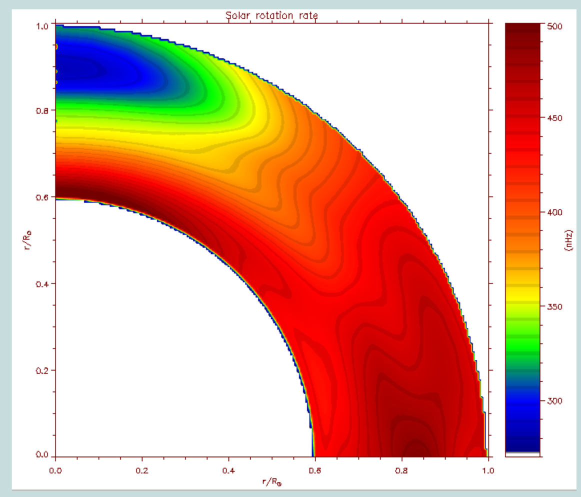

Fig 3: Internal Solar rotation rate inferred by inverting frequency splittings from PICARD/SODISM intensity images over the period from April 16 to November 10 2011. The solution is not reliable bellow 0.6 Solar radius and is poorly constrained close to the pole. Only the symmetric part with respect to the equator can be obtained. The inverse method used is a 2D Regularized Least Square (Corbard et al. 1997)

Limb Seismology

Every 2 minutes, the full resolution of PICARD/SODISM images are kept in an annulus of 22 pixels around the Solar limb (increased to 31 pixels since April 2012). In April 2011 and April 2012 , 3 consecutive days were dedicated to helioseismic measurements at 535.7 nm without interruption for the other PICARD objectives. These sets with a duty cycle above 95% have been used in order to study the expected mode amplification at the extreme limb (Appourchaux et al. 1998b, Toutain et al. 1999, Toner et al., 1999). Intensity data from SOHO/MDI and SDO/HMI were also used for comparison.

The transformed applied on the limb consists in making the Fourier transform ($e^{i\ell'\rho}$) along the limb using the polar coordinates where ρ=1 at the disk center and ρ=0 at the limb.

Figure 4 shows the comparison between the ℓ-ν diagram obtained from classical spherical harmonic transform of full images (top) and the ℓ'-ν diagram (middle) resulting from the limb transform as described above. A frequency shift between ridges of the same radial order is clearly seen (bottom).

We carried out simulations in order to understand this shift and the link between the two diagrams. For a given ℓ' it can be shown that the limb response are non zero for value of l higher than ℓ'. Since the mode frequencies increase with the degree, the leaks will appear at higher frequencies than the original anticipated frequency. The leaks will then appear as an asymmetry at higher frequency with a decreasing amplitude when ℓ increases. This is indeed what is shown in *figure 5* where the observed ridge profiles obtained from PICARD/SODIM and SOHO/MDI intensity data are compared to the simulated profiles. From these simulations we are able to understand:

- why the peak in the ℓ'-ν diagram is shifted with ℓ (the shift with the original ℓ-ν ridge increases as ℓ increases),
- why the peak gets closer to the original ridge as we get closer to the limb,
- why the ℓ'-ν ridge leaks towards higher frequencies.

Figure 6 (left) shows that the energy in the p-mode range peaks at the extreme limb as was already seen using MDI intensity images (Toner et al. 1999) or the guiding pixels of SOHO/LOI (Appourchaux et al. 1998b). If we normalize this by a proxy of the noise level obtained by integrating the energy in the low frequency band *(right panel)*, we see that we effectively have an amplification of the Signal to Noise ratio at the extreme limb for MDI and HMI . This peak is slightly shifted inward for SODISM but this may be an instrumental effect. This needs further investigations.

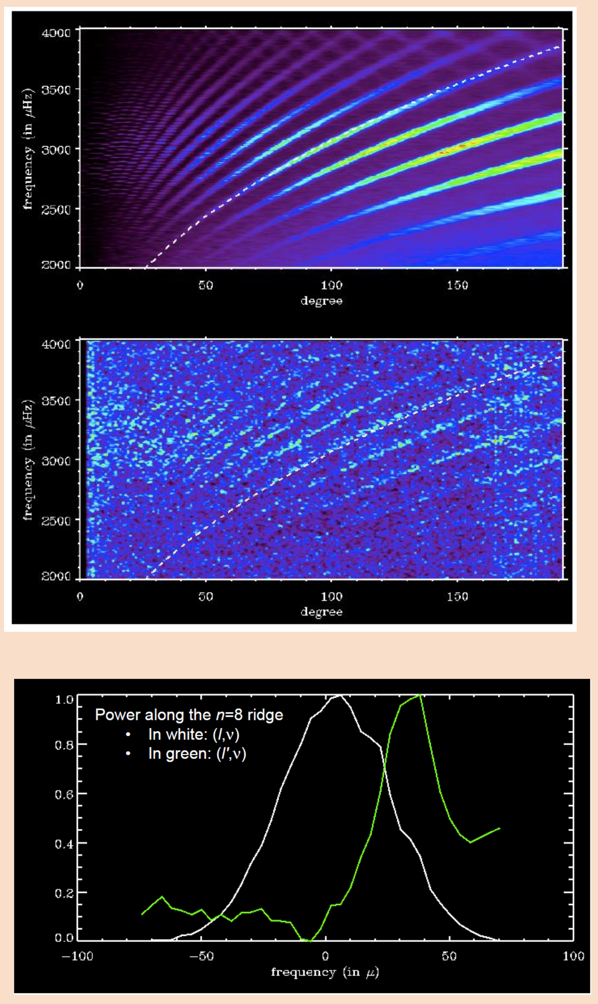

Fig 4: Classical spherical harmonic transform of full images (ℓ-ν diagram) (top) and limb transform of limb pixels (ℓ'-ν diagram) (middle). The powers along the n=8 ridge (dashed line) for both cases are shown on the bottom panel clearly showing a frequency shift.

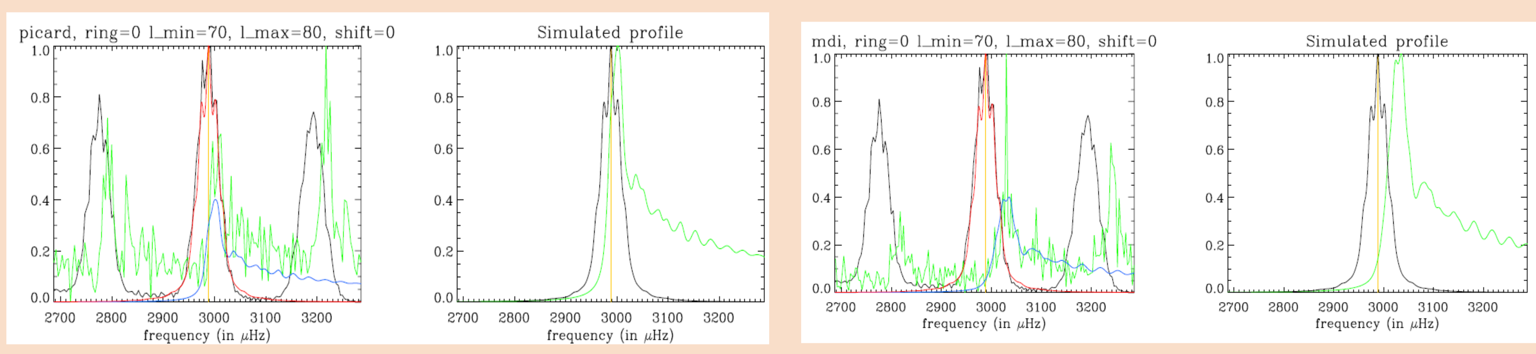

Fig 5: Comparison between observed (left) and simulated profiles (right). The two panels on the left are for PICARD/SODISM while the two on the right are for SOHO/MDI. Black and green lines are ridges in the ℓ-ν and ℓ'-ν diagrams respectively. Their fit around 3mHz are shown by the red and blue lines respectively.

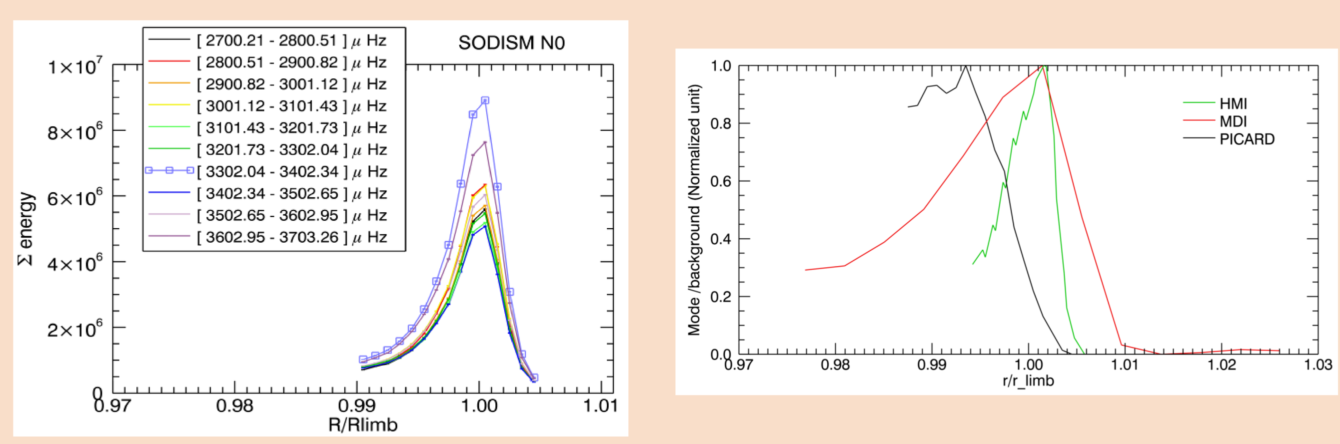

Fig 6: Left: spectral energy level integrated in several frequency ranges of the 5-mn oscillations envelope. Right: energy of the 5-mn envelope normalized by the low frequency energy, for SODISM, SOHO/MDI and SDO/HMI. As far as SODISM is concerned, the amplification curve is displaced toward the inner part of the limb. This could be due to an instrumental effect not well taken into account in the data reduction pipeline. Note the narrower profile in the case of HMI, consequence of a better PSF.

Conclusions

- These first helioseismic analyses of SODISM images demonstrate that we are able to extract useful information from this dataset. We were able to fit mode parameters for a wide range of modes up to ℓ=115 . The fitted peak asymmetries and frequency splittings are consistent with what is known from previous studies.
- We were able to carry out a first inversion of the rotational splittings and to infer the internal rotation rate down to the tachocline, the steep gradient of which is clearly seen in SODISM intensity data.
- The signature of p-modes can also be seen in limb data and we detect a signal amplification at the extreme limb. We have carried out simulations that explain most of the features of the power spectra observed at the limb when compared to full images spectra.
- The calibration procedure is however very complicated and we have to face strong instrumental and orbital effects that affect both the photometric signal and the geometry of the solar images.
- We are still working on improving our calibration procedure and we hope that PICARD will be extended at least one year in order to gather more intensity data that can be compared and cross-calibrated with SDO/HMI intensity and velocity images.

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