Helioseismology program for the PICARD satellite

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The PICARD mission is a CNES micro-satellite to be launched in 2009. Its goal is to better understand the Sun and the potential impact of its activity on earth climate by measuring simultaneously the solar total and spectral irradiance, diameter, shape and oscillations. We present the scientific objectives, instrumental requirements and data products of the helioseismology program of PICARD which aims to observe the low to medium l p-mode oscillations in intensity and search for g-mode oscillation signatures at the limb.

1 Introduction: the PICARD mission

The micro-satellite PICARD from the French spatial agency (CNES) is scheduled to be launched in 2009 on a Sun synchronous orbit. The mission is named after the french astronomer Jean Picard (1620–1682) who did the first precise solar diameter measurements in order to determine the eccentricity of Earth orbit. The main objective is to measure the solar diameter, oblateness and limb shape with an unprecedented accuracy (few milliarcseconds per image) in order to study their possible variation with activity and to give an absolute reference for future measurements by using star distance calibration. This will be achieved in three different wavelengths (535.7, 607 and 782 nm) by using the SOlar Diameter Imager and Surface Mapper (SODISM) which is an imaging 11 cm Cassegrain telescope equipped with a 2048×2048 CCD detector and an internal angular scale reference (Assus et al. 2008). The payload also includes the SOVAP (SOlar VARIability PICARD) instrument and the PREcision MOonitor Sensor (PREMOS). SOVAP is equipped with a small Bolometric Oscillation Sensor (BOS) and a differential absolute radiometer (DIARAD) for Total Spectral Irradiance (TSI) measurements. PREMOS is equipped with three Sun PhotoMeters (SPM) with four channels each which will monitor together the spectral irradiance in UV (215 and 268 nm) visible (535 nm) and near IR (607 and 782 nm), and two absolute radiometers of type PMO6 for TSI measurements.

The full description of the mission, its payload, and its main scientific objectives including climate change, solar physics and space weather can be found in several recent papers (Buisson et al. 2006; Thuillier et al. 2006). We will focus here on the helioseismology program of the mission. As a matter of fact, many specifications related to what will be the PICARD helioseismology data products have been improved during the past year and are not fully represented in the references above. Being one year and half before the scheduled launch, we can now think that these specifications and data products will not change significantly anymore.

2 Science objectives for the PICARD helioseismology program

As mentioned above, the primary goals of the PICARD mission are astrometry and radiometry for the accurate and simultaneous measurements of the solar shape and irradiance and their variations. It became however immediately clear that the specific design of the SODISM telescope, which has to be thermally controlled and optimized for distortion-free observation at the limb, should also be used for monitoring solar oscillations in intensity (e.g. Damé et al. 1999). As we shall show, the requirements for doing seismology with SODISM are high in terms of both the required instrumental performance and the amount of data to transfer. There are however two main reasons why we believe these efforts had to be done.

First, it has been shown that observing the solar oscillations at the limb can be in some cases more advantageous than using full-disk data. Toutain, Berthomieu & Provost (1999) have shown that the variations of the optical thickness near the limb dominate the temperature changes and therefore the p- and g-mode signals for continuum intensity observations should peak at the solar limb. This effect was seen for p modes with Solar and Heliospheric Obser-
analyzing 72 hours of MDI full disk continuum intensity images obtained in July 1996. The two vertical lines show the area that will be observed every 2 min with a resolution of 22 pixels of 1′′/pixel resolution over rings centered on the limb inflexion point.

Second, while it has been demonstrated that the signal to noise ratio in the p-mode frequency domain is generally better in velocity than intensity both measurements are complementary and should be used together whenever possible. The profiles of oscillation mode in the power spectra have been found to be asymmetric rather than of simple Lorentzian shape and the asymmetry is reversed between intensity and velocity signals. The asymmetry itself can be related to the nature or depth of the acoustic sources (e.g. Duvall et al. 1993) while the asymmetry reversal is linked to the effect of a background component correlated to the modes (e.g. Nigam et al. 1998). By fitting intensity, velocity, their phase difference and coherence signals simultaneously, we are therefore able to better understand the correlated background noise and to better interpret the fitted frequencies and frequency splittings, which in turn should lead us to more reliable estimates of the internal dynamics and structure (Severino et al. 2001; Barban et al. 2004). Like for MDI however, the telemetry limits the amount of data we can transmit continuously at the 1 min cadence needed for studying p modes and we will have to degrade our images and build the so-called Macro-Pixel (MP) images.

These two aspects of the observing program of PICARD together with the radiometric and metrologic measurements will allow us to address several fundamental issues in solar physics, which are summarized below.

2.1 Structure and dynamics of the nuclear core

The structure and dynamics of the nuclear core are not yet determined by the techniques of helioseismology. The information provided by the p modes on that region of the Sun is not as precise and as significant as it would be with the g modes. Since the beginning of helioseismology, the detection of g modes has been the most challenging quest in our field. There were claims of g-mode detection (Delache & Scherrer 1983; Thomson, Maclennan & Lanzerotti 1995), none of which were confirmed. Since the conception of the SoHO mission, one of the goals of this mission was to detect g modes. The Phoebus group set an upper limit to the g-mode amplitude of 10 mm/s in velocity or 0.5 ppm in intensity at 200 µHz (Appourchaux et al. 2000). Since then, this lower limit has been even decreased down to about 4.5 mm/s for a 10-year observation with a singlet, and down to 1.5 mm/s for a multiplet (Elsworth et al. 2006). Recent g-mode detection claims rely upon a new detection technique derived from the asymptotic properties of g-mode periods derived from theoretical models (García et al. 2007). They reported patterns of \( l = 1 \) g modes with a possible amplitude of 2–3 mm/s (10 \( \sigma \) value) below 100 µHz, and having a lifetime of a few months. The detection of a frequency at 220.7 µHz was also reported by Antonio Jiménez (private communication; see also García et al. 2008).

The required data to progress in this field are measurements of the frequencies of the gravity and mixed modes and their splittings. Because they have very low amplitudes at the surface, detection techniques will use all the a-priori information available on these modes (see Appourchaux 2008, on how to use a Bayesian approach for detecting g modes). Their detection therefore relies also on a deep understanding of their excitation and damping mechanisms, the properties of the atmospheric layers where we try to detect them, the solar noise (granulation and super-granulation) and of all the other contamination effects which may affect the mode propagation and visibility such as the surface magnetic structures and their evolution with activity.

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2.2 The solar dynamo, tachocline and torsional oscillations

One of the major challenges in solar physics is to understand the origin of the magnetic activity cycle of the Sun. Helioseismology does not give direct access to the internal magnetic field strength but it is a very powerful tool to infer the internal rotation rate, and some useful information on the magnetic field can also be deduced from its predicted interaction with the observed velocity field.

The tachocline is a thin shear layer at the interface between the convection zone and the radiative interior, in which it is likely that a strong magnetic field is built as a result of the dynamo $\Omega$-effect. From the study of its properties (structure, extent, precise location and latitudinal shape) we can derive not only the precise profile of the rotational shear but also get some hint on the shape and strength of the magnetic field at this depth. Moreover monitoring continuously the tachocline parameters and their potential time variation is of major importance for our understanding of the solar cycle (see e.g. Corbard et al. 2001 for an overview).

So far, the only demonstrated way to probe this layer is by the use of global helioseismology methods. The tachocline is sensed mostly by $p$ modes with degrees $20 < l < 60$ but these modes are also sensitive to the layers of the convection zone up to the photosphere and therefore, in order to isolate the contribution of the tachocline, one need to analyse not only these modes but also all the higher degree modes.

In the convection zone we can also detect and follow the so-called torsional oscillations: when the mean internal rotation profile is subtracted from the profile inferred at different times, the residual shows bands of enhanced rotation rate that migrate toward the equator during the increasing phase of activity. These torsional oscillations are seen deep in the convection zone (Howe et al. 2000) and are roughly in phase with the well known migration of sunspots forming also bands migrating toward the equator usually represented by the butterfly diagram. It is very likely that we have here a direct observation of the back reaction of the dynamo magnetic field on the rotational profile, from which the toroidal field originates within the tachocline (Covas et al. 2000). Again, it is very important to study and monitor this phenomenon over time because it allows us to constrain our models of the interplay between magnetic field and convection (e.g. Petrovay & Forgács-Dajka 2002; Covas et al. 2004). These observations are made possible by helioseismology by measuring the medium to high degree modes that are sensing the convection zone and near surface layers.

2.3 Fundamental ($f$) modes and the solar radius

The photospheric radius of the Sun that will be measured with space with PICARD in different wavelengths with unprecedented accuracy (Thuillier et al. 2006) is also an important parameter for helioseismology. It can be used as a calibration radius i.e. for calibrating the location where the temperature is equal to the effective temperature ($T = T_{\text{eff}}$) in solar models. These models are then used to predict oscillation mode frequencies. The frequencies of the $f$ modes are of particular interest because, unlike $p$-mode frequencies, they depend mainly on the surface gravity directly related to the radius and less on the internal physics of the Sun. Thus, an observed discrepancy between the predicted and observed $f$-mode frequencies can be used to adjust the calibration radius to a so-called seismic radius, that reproduces the observed frequencies better. Following this procedure with the $f$-mode frequencies observed by MDI medium-$l$ program, Schou et al. (1997) were able to deduce that the calibration radius should be reduced by 300 km. Simultaneous measurements of the photospheric radius and $f$-mode frequencies are therefore of great interest in order to constrain our models. Our goal is to measure $f$-modes frequencies with SODISM using both the limb and MP images. It is interesting to notice that Toner et al. (1999) using MDI limb data were able to reveal a low frequency $f$ mode that was buried in the noise when using full disk data. Figure 4 (bottom), discussed in Sect. 4.3, also reveals the $f$-mode ridge for very high degree $l > 350$, by using only one day of data.

It is important to notice that even if the seismic radius definition is model dependent while the photospheric one is not, any useful interpretation of the photospheric radius and its variation in terms of internal solar physics and magnetic activity also requires a model of the photospheric layers. The limb data would be useful to constrain our knowledge on solar atmospheric models only if these were built with enough accuracy. In this respect, it is important to consider the 3D time-dependent hydrodynamic simulations of solar surface, as done by Stein & Nordlund (1998). Such numerical simulation succeeded in reproducing solar granulation topology and line profiles (depth, shifts and asymmetries) with a great realism. They have been used recently to calculate stellar limb darkening (Aufdenberg et al. 2005; Bigot et al. 2006), which have shown the need to use a 3D approach rather than the traditional 1D hydrostatic one. Even if these simulations made a considerable step toward realistic modeling of the solar surface, there is still a need for improvements to fit the outermost layers at the limb, like, for example, including Non LTE radiative transfer, opacity sampling and magnetic field effects.

3 Specifications for doing helioseismology with SODISM

Without the knowledge of the amplitude of the $g$ modes, particularly through the (unknown) amplification factor at the limb, it is not possible to derive the stability level required for their detection. The philosophy, already used for SoHO, is to specify the instrumental noise significantly below what is expected for the solar noise itself. Therefore, a value of 0.01 ppm$^2$/Hz was chosen for the instrumental noise because it is below the solar noise level observed with the LOI/SoHO in the $p$-mode band (Appourchaux et
al. 1997) by a factor 10. This level was then translated into technical stability requirements, for each potential source of perturbation, knowing that it could be somewhat relaxed in the g-mode spectral range only, due to the increase of the solar noise at low frequency. In case of an unachievable stability of some sub-systems, the philosophy is to monitor and proceed with aposteriori corrections, thanks to well defined housekeeping data.

3.1 Sampling

The operational sequence allows a 2-minute sampling for limb measurements and a 1-minute sampling for the Macro-Pixel images. It is significantly better than the originally planned sequence, thanks to a great work of optimization led by the project team (laboratories and CNES). The timing is controlled by the On Board Computer (OBC), based on a 1 Hz counter. As the counter cannot be perfectly tuned to 1 Hz, the OBC delivers to the payload the date associated to the pulses, expressed in the Coordinated Universal Time (UTC) frame. The precision required for the eigenmode frequencies is better than the 3-year frequency resolution, i.e. is of the order of a few nHz. It is achievable if we can get rid of the drift of the oscillator, which will be realized by a clock resynchronisation once a week. The performances of the system developed for PICARD are the following: the residual drift is 20 ms/week, the precision of the resynchronisation is about $±30$ ms, and the jitter on the 1-minute pulse itself is about 3 ms (3-$\sigma$ value). We have checked with simulations on pure sine waves that the aliasing produced by this sampling noise is only 0.1% of the energy of the peaks. We have also checked that the UTC reference will not cause too much trouble in case of leap seconds during the mission, but it will have a huge impact on the analysis of the phases of the modes and on coordinated analysis, for example with data coming from the Solar Dynamics Observatory (SDO) which is using the better and proper International Atomic Time (TAI) reference (see also Sect. 5).

3.2 Photometry

The main noise on the photometry is expected from exposure time and electronic gain fluctuations. For a 2-minute sampling, a tenth of the solar noise corresponds to a 9 ppm (standard deviation) photometric fluctuation, which means that the product (exposure time $\times$ electronic gain) should have this stability or should be known with this accuracy. If the exposure time was dominant, the requirement would translate entirely into 0.072 ms (8-second integration). The performance tests of the SODISM shutter show that a 0.050 ms standard deviation around the mean exposure time is achievable, which meets our requirement. Moreover, even in the case of an aging of the shutter, the knowledge of the exposure should be kept accurate to $±25\mu$s, which will allow posterior corrections of the photometry. As far as the pointing stability is concerned, our calculations led to a 0.1 arcsecond stability for the image on the CCD. The attitude and orbit control system of the platform being not accurate enough, a fine pointing is realized by SODISM itself, thanks to a device acting on the primary mirror.

3.3 Operational mode, duty cycle and coding

The satellite is nominally pointed with the reference axis of the CCD aligned with the solar rotation axis. Several other modes will be occasionally operated, mainly for calibration purposes. The main depointings will occur with a few months occurrence, either for observing a stellar field (reference angle for Sun diameter calibration), or for observing the Sun with 30-degree steps roll angles (optical distortion calibration). Eclipses due to the orbit will also reduce our duty cycle. For a typical 700 km orbit, 90 days per year will have eclipses, which duration will reach 20 minutes at maximum. We simulated the loss in duty cycle as well as the aliases produced by the operational sequences, included eclipses and statistical losses in the telemetry flux: the duty cycle remains higher than the specified 90%, and the aliases are not significant as shown by Fig. 2. As far as digitization is concerned, we performed simulations on pure sine waves embedded in the photon noise expected with SODISM, and derived that a minimum of 14-digit coding is preferable in order to reduce the occurrences of appearance of ghost peaks in the power spectrum. This is consistent with the 16-digit converters used by SODISM. The images are eventually lossless compressed before transmission to the Earth, particularly to the Mission Center located in Brussels.

3.4 Maximum spherical harmonic degree ($l$)

The objective for the medium-$l$ program is to detect and resolve modes with angular degrees from $l = 0$ up to at least $l = 250$ which is the value reached for p modes with the MDI medium-$l$ program in velocity (Scherrer et al. 1995).
For f modes however MDI Doppler velocity images allow us to measure their frequencies and frequency splittings up to \( l = 300 \) and we shall try to reach also these modes with PICARD intensity images. The signature of modes with higher degrees can be detected in the power spectra (Fig. 4 shows for instance \( p \)-mode power on ridges up to \( l = 400 \)) but these modes cannot be resolved individually even with long time series because the frequency difference between the neighboring modes become smaller than their linewidths. They are also strongly affected by the inevitable leakage resulting from the fact that the spherical harmonics are not forming an orthogonal basis on the single hemisphere we observe. These high degree modes \((l > 300)\) while interesting for studying the immediate subphotospheric layers of the Sun (e.g. Rabello-Soares et al. 2000) would require to keep the full resolution of SODISM images which cannot be done with PICARD given our telemetry limits. The measurement of frequency and frequency splitting for degrees up to \( l = 300 \) will allow us to study the tachocline, the convection zone and its torsional oscillations up to about 0.98 solar radius.

### 4 Scientific operation modes and data products

#### 4.1 Low degree \( p \) modes from radiometric sun-as-a-star data

The data products that will be used for helioseismology are summarized in Table 1. The radiometers of SOVAP and PREMOS integrate the irradiance coming from all the surface of the Sun. In other word the Sun is seen as one would see a non-resolved star. Such observations give access to modes with spherical harmonics \( l \leq 4 \) only. These measurements, obtained at different wavelengths, are a continuation and extension of what is done with VIRGO on SoHO (Fröhlich et al. 1995). For comparison, VIRGO is equipped with a three-channel full-SPM, which record the solar spectral irradiance through 5 nm wide filters centered at 402 nm, 500 nm and 862 nm at a cadence of 60 s. It can record the radiation with 12 resolution elements on the solar disk using the LOI and, it contains two different active-cavities radiometers (DIARAD and PMO6). VIRGO has allowed the study and follow-on of \( p \) modes \( l < 10 \) during the past 11 years and was able to reveal a clear and stable signal in the \( g \)-mode band at 220.7 \( \mu \)Hz as reported by García et al. (2007). The study of the solar noise at different wavelengths (Fröhlich et al. 1997) is also an essential tool as the solar noise is the limiting factor in the search of the \( g \) modes. With PREMOS and SOVAP instruments, we shall follow that method in other spectral domains and higher sampling rate (see Table 1). The much higher resolution provided by SODISM compared to the LOI (256\(^2\) pixels instead of 12) will furthermore allow us not only to deconvolve effects of different photospheric features on the spectral irradiance at 535.7 nm but also to carry an original program for \( g \)-mode search at the limb and a full medium-\( l \) program in intensity for observing \( p \) modes up to at least \( l = 250 \).

#### 4.2 Limb seismology and \( g \)-mode search

SODISM will provide limb intensity data on a 22-pixel wide ring centered on the inflexion point of the limb-darkening function. This corresponds to the area comprised between the two vertical dashed lines on Fig. 1. It should allow us to clearly identify the increase of power near the limb. The position of the limb on the CCD will change as a result of the apparent solar diameter variations due to the elliptic orbit of the Earth. The maximum rate for the displacement of the limb through the year is of 0.25′′/day and therefore the mask will be adjusted twice a week in order to follow that movement and to insure that it is always centered on the inflexion point within less than a pixel (i.e. 1′′). These rings will be recorded every 2 min with an exposure time of 8 s. The 2 min cadence is imposed by telemetry limitations. An higher cadence of 1 min would be in principle preferable to avoid the aliasing of the existing high frequency modes between 4.33 mHz and the solar acoustic cutoff onto the lower frequencies. However, the very low frequency band (below 1.5 mHz) that we want to explore with these data should not be significantly affected by the aliasing. These data will be used mainly to search for gravity, mixed and low frequency acoustic modes taking advantage of the expected amplification factor at the limb but will also contribute to the solar radius measurements by providing inflexion point positions extracted every 2 minutes.

#### 4.3 Medium-\( l \) program

As explained in Sect. 3.4, our objective with PICARD is to observe in intensity modes with degree up to at least

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Data Type</th>
<th>Wavelength [Bandpass] (nm)</th>
<th>Sampling [Exposure] (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SODISM</td>
<td>22'' wide rings of limb pixels (1''/pixel)</td>
<td>535.7 [0.5]</td>
<td>120 [8]</td>
</tr>
<tr>
<td></td>
<td>256\times256 Images (8''/pixel)</td>
<td>535.7 [0.5]</td>
<td>60 [8]</td>
</tr>
<tr>
<td>PREMOS</td>
<td>Spectral Irradiance</td>
<td>535.7 [0.5]</td>
<td>10 [10]</td>
</tr>
<tr>
<td></td>
<td>782.3 [1.7]</td>
<td>10 [10]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>607.2 [0.8]</td>
<td>10 [10]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>268 [?]</td>
<td>10 [10]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>215 [?]</td>
<td>0.1 [0.1]</td>
<td></td>
</tr>
<tr>
<td>PM06</td>
<td>TSI</td>
<td>All</td>
<td>120 [20]</td>
</tr>
<tr>
<td>SOVAP</td>
<td>DIARAD</td>
<td>TSI</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td>BOS</td>
<td>TSI</td>
<td>All</td>
</tr>
</tbody>
</table>

Table 1 Measurements usable for helioseismology.
Fig. 3 (online colour at: www.an-journal.org) Power spectra ($l$-$\nu$ diagram) obtained from 1 day (1997 May 1) of the MDI full disc continuum intensity data reduced to $10''$/pixel resolution by using either the Gaussian binning scheme of Kosovichev et al. (1997) (top) or a simple binning over $5 \times 5$ MDI pixels (bottom).

Fig. 4 (online colour at: www.an-journal.org) Power spectra ($l$-$\nu$ diagram) obtained from 1 day (1997 May 1) of the MDI full disc continuum intensity data reduced to $8''$/pixel resolution by using either the Gaussian binning scheme of Kosovichev et al. (1997) (top) or a simple binning over $4 \times 4$ MDI pixels (bottom).

$l = 250$ and possibly $l = 300$ which corresponds to what was achieved in velocity by MDI medium-$l$ program. Like for MDI, telemetry limits impose to degrade our images to a lower resolution on board before they are transmitted. The choice of the size of the MP images is constrained by our telemetry capacities and the time needed for their on-board computation. Several options have been considered. First, the MP can be constructed either by a simple average of individual (i.e. $1''$) pixels or by using a Gaussian filter. This choice will have an impact on the spatial aliasing and on the time needed for on-board computations. Second, we can choose to compress by a lossy or lossless compression scheme. Lossless compression has a cost in terms of computation time but, of course, no impact on the science products. Lossy compression while providing better compression rate needs to be fully tested in order to insure that it would have no impact in the temporal and spatial frequency ranges of interest for helioseismology.

MDI original images are $1024 \times 1024$ with a a resolution of 2 arcseconds per pixel. For the medium-$l$ program
they are reduced to images with 10 arcseconds per pixel by using a Gaussian binning over 5 × 5 pixels (Kosovichev et al. 1997). A similar scheme using Gaussian binning over 10 × 10 pixels of the SODISM original 2048 × 2048 images has been considered in order to reach similar resolution and therefore l values. Figure 3 (top) shows the l-ν diagram obtained by analyzing one day of MDI full disk continuum intensity data using the same Gaussian binning scheme as used for MDI medium-l velocity program. Figure 3 (bottom) shows the analysis of the same data but using straight averages of 5 × 5 MDI pixels without applying Gaussian mask. The comparison of the two figures demonstrates that the Gaussian binning is indeed useful to suppress spatial aliasing contamination of the modes with harmonic degree below l = 300. The on-board computations needed to apply the Gaussian mask are however time consuming and it is likely that we will rather increase the resolution from 10 to 8 arcseconds per pixel but do only raw averages of the 8 × 8 pixels. Figure 4 (top) was obtained by using that last scheme and it shows that, with this resolution, we are not sensitive to the spatial aliasing for modes l < 300 even if we are not using the Gaussian binning. Moreover, a more detailed analysis shows that the signal to noise ratio is better with simple averaging than with lower resolution and Gaussian binning. For completeness, Fig. 4 (bottom) shows what one would obtain by using Gaussian binning to form 8 arcsecond pixels. In that case there is no apparent contamination of the spectra for degrees up to l = 400. In all the cases a compression of the MP images is needed before they are transmitted. The compression rate of about 2.1 reached by a lossless compression method using differential coding is enough to satisfy our telemetry constraints. The results of our tests performed using a lossy compression method might however be useful to some other future missions with limited telemetry such as Solar Orbiter. They are given in the Appendix.

In conclusion, PICARD medium-l data will consist on MP images made of 2562 pixels with a resolution of 8″/pixel obtained by raw binning of the original images. These MP images will be produced every minute. If for some reason the telemetry limits do not allow us to reach this resolution, we will go down to 10″/pixel or less. The Gaussian binning will probably not be implemented on board and therefore, even if the resolution needs to be lowered, only simple averages will be possible on board. Another important point to notice is that while MDI medium-l images are restricted to a disk that covers 90% only of the full disk, the limb pixels are kept for PICARD medium-l program. This will avoid the spatial leakage from adjacent modes that are induced by the use of a reduced observed portion of the disk. We can do this in the case of PICARD because we expect these limb pixels to carry enhanced signal in intensity while they are known to carry essentially noise in the velocity data of MDI.

5 Synergies with the SDO

Scheduled for launch in 2008 SDO will be the first mission for NASA’s Living With a Star (LWS) Program, a program designed to understand the causes of solar variability and its impacts on Earth. An overview of the science investigation program for the Helioseismic and Magnetic Imager (HMI) of the SDO is given by Kosovichev at al. (2007). The science objectives of PICARD and HMI are similar and their measurements are complementary. PICARD will provide the radiometric and metrologic measurements that SDO is lacking for the long term studies of the solar variability while SDO will provide 3D vector magnetic field maps that should be used for the irradiance models needed to interpret PICARD radiometric data. HMI will also provide much more complete data for the study of the solar internal structure and dynamics through helioseismology. In short, HMI is equipped with a 4096 × 4096 CCD camera and will get for each pixel 5 or 6 filtergrams across the spectral line Fe I (617.3 nm), which will be combined on the ground to provide us every 50 seconds both Doppler velocity and continuum intensity images with an angular resolution of 0.5″/pixel. The main focus with these data will be for local-area helioseismology methods (see Gizon & Birch 2005 for a review) in order to probe in 3D and high resolution the structure and dynamics of the near surface layers and possibly down to the tachocline. The Doppler velocity images will also be used for a global helioseismology program similar to MDI medium-l but with enhanced capacities as the full resolution of the images can be used and the cadence is increased. There is however no plan so far to use HMI intensity data for helioseismology because these are much noisier than the Doppler shift data. They will be used to extract solar limb parameters and produce brightness feature maps useful for identifying sources of irradiance and eventually for some other particular tasks such as testing the inclined field effect in sunspots. As we have discussed above, we think however that there is a strong interest in studying both velocity and intensity signals for helioseismology and our plan is to develop the pipeline for PICARD intensity medium-l and limb data in such a way that it can also be used to analyse HMI intensity data and perform inter-comparison.

6 Summary

While PICARD main objective is not helioseismology, we believe that we have reached the capacity of doing an interesting helioseismology program with two aspects:

1. Gravity mode search and low frequency, low degree p-mode analysis using both the limb helioseismology program of SODISM and the radiometric measurements of PREMOS and SOVAP.
2. A medium-l intensity program for monitoring p and f modes with degrees up to l = 300.
This should allow us to study the dynamics and structure of the solar interior from the nuclear core up to 0.98 solar radius and to record their variation during the time of the mission. This will nicely complete the TSI, diameter and limb shape measurements provided simultaneously by PI-CARD and contribute to improve our understanding of the origin of the solar activity cycle. Moreover, the intercomparison and cross analysis with SDO/HMI velocity and intensity data will provide useful information on the instrumental and solar background noises and therefore a more reliable interpretation of our results.

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A Tests on using a lossy compression method

Figure A1 shows the relative difference in % between the initial $l$-$\nu$ diagram and the one obtained from the reconstructed images after using a lossy compression based on wavelet decomposition (Langevin & Forni 2000). The relative difference remains very small on the ridges of interest but there is an important variation with frequency especially above the solar cutoff frequency (5 mHz). Up to 3.5 mHz the relative difference integrated over all the $l$ values remains bello $0.5\%$ and then it increases to reach $6\%$ at 5 mHz. When integrated over all frequencies below the cutoff frequency, the relative difference is less then $0.6\%$ for $50 < l < 250$ but reach up to $2\%$ for $l < 30$. These first tests look promising for a potential use of a lossy compression with high compression rate (4 in our tests) for future mission with limited telemetry. A more detailed analysis using longer time series is however needed in order to check precisely how much the lossy compression method could affect the fitted mode parameters and background noise in the domain of interest for a particular mission.

Fig. A1 (online colour at: www.an-journal.org) Relative difference in % between the $l$-$\nu$ diagram of Fig. 4 (bottom) and the one obtained in the same way but using images reconstructed after lossy compression.