SYMPA, a dedicated instrument for Jovian Seismology. 
II. Real performance and first results

Patrick Gaulme$^1$, F.X. Schmider$^1$, Jean Gay$^1$, Cédric Jacob$^1$, Manuel Alvarez$^3$, Mauricio Reyes$^3$, Juan Antonio Belmonte$^4$, Eric Fossat$^1$, François Jeanneaux$^1$, and Jean-Claude Valtier$^1$

$^1$ Laboratoire FIZEAU, Universitè de Nice Sophia-Antipolis, CNRS-Observatoire de la Côte d’Azur, F-06108 Nice Cedex 2
$^2$ Observatorio Astronómico Nacional, Instituto de Astronomía, Universidad Nacional Autónoma de México, Apto. Postal 877, Ensenada, B.C., México
$^3$ Instituto de Astrofísica de Canarias, Tenerife, Spain
$^4$ THEMIS Observatory, La Laguna, Tenerife, Spain

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ABSTRACT

Context. Due to its great mass and its rapid formation, Jupiter has played a crucial role in shaping the Solar System. The knowledge of its internal structure would strongly constrain the solar system formation mechanism. Seismology is the most efficient way to probe directly the internal structure of giant planets.

Aims. SYMPA is the first instrument dedicated to the observations of free oscillations of Jupiter. Principles and theoretical performance have been presented in paper I. This second paper describes the data processing method, the real instrumental performance and presents the first results of a Jovian observation run, lead in 2005 at Teide Observatory.

Methods. SYMPA is a Fourier transform spectrometer which works at fixed optical path difference. It produces Doppler shift maps of the observed object. Velocity amplitude of Jupiter’s oscillations is expected below 60 cm s$^{-1}$.

Results. Despite light technical defects, the instrument demonstrated to work correctly, being limited only by photon noise, after a careful analysis. A noise level of about 12 cm s$^{-1}$ has been reached on a 10-night observation run, with 21% duty cycle, which is 5 time better than previous similar observations. However, no signal from Jupiter is clearly highlighted.

Key words. planets and satellites: formation, Jupiter: oscillations, methods: observational, instrumentation: interferometer, techniques: spectroscopic

1. Introduction

Due to its great mass and its rapid formation, Jupiter has played a crucial role in shaping the Solar System. Two scenarios are generally proposed for the formation of giant planets: the nucleated instability (Safronov & Ruskol 1982) and the gravitational instability models (Cameron 1978 and Mayer et al. 2002). An efficient constraint on the formation scenario would be given by measuring the total amount of heavy elements inside Jupiter and the size of the planetary core. Moreover, the knowledge of Jupiter’s internal structure would constrain the high pressure hydrogen equation of state, which is still inaccurate, and would particularly solve the question of the nature of the metallic-molecular phase transition (e.g. Guillot et al. 2004). Gudkova & Zharkov (1999) showed that the observation of oscillation modes up to degree $\ell = 25$ would strongly constrain Jupiter’s internal structure by exploring both the hydrogen plasma-phase transition and the supposed core level.

Attempts to observe Jovian oscillations have been brought since the mid 1980’s, thanks to different techniques. On one hand, Deming et al. (1989) have looked for oscillation signature in thermal infrared. Unfortunately, their infrared detectors, not enough sensitive, did not detect any signal. On the other hand, oscillations were sought in velocity measurements, obtained by Doppler spectrometry. Schmider et al. (1991, hereafter S91) used sodium cell spectrometer and Mosser et al. (1993, 2000, hereafter M93 and M00) the Fourier transform spectrometer FTS (at CFHT, Hawaii) at fixed optical path difference. An excess of power has been brought out in the spectrum at frequency range $[0.8-2]$ mHz, as well as the large separation of oscillation $p$-modes around 140 $\mu$Hz. Nevertheless, the oscillation modes have never been individually identified, hindering any constraint about the internal structure.

SYMPA is an instrument dedicated to Jovian oscillations, which concept and performance have been described in paper I (Schmider et al. 2007). For the first time, a specific instrument dedicated to Jovian oscillations was developed, including imaging capability. Indeed, full disc observations do not permit to distinguish modes of degree higher than 3. Moreover, the broadening of the solar lines, due to the fast rotation of Jupiter, reduces drastically the sensitivity of such measurements. The instrument, a Fourier tachometer, is composed of a Mach-Zehnder interferometer which produces four images of the planet, in the visible range corresponding to three Mg solar absorption lines at 517 nm. The combination of the four images, in phase
quadrature, allows us to retrieve the phase of the incident light, which is related to the Doppler shift generated by the oscillations.

Two instruments were built at Laboratoire Fizeau (Nice University). Three campaigns were lead simultaneously on two sites: in 2003, at San Pedro Martir (Mexico) and Calern (France) observatories; in 2004 and 2005, at San Pedro Martir and Teide (Canaries) observatories. 2003 campaign was mainly dedicated to technical commissioning. In Canaries, bad weather conditions have strongly limited the efficiency of the 2003 and 2004 campaigns, whereas the 2005 campaign benefited of better conditions.

In this paper we present the data processing, the real performance and the first results, obtained during the 2005 run at Teide observatory. The processing of the San Pedro Martir data and the combined analysis of both observing 2005 network campaign will be considered in a future work. After a short presentation of the observing conditions (Sect. 2), Sect. 3 presents the process of the data analysis. We expose in Sect. 4 all the steps for an accurate calibration of the data. Sect. 5 is devoted to the further of the data reduction, for the measurement of velocity maps. The analysis of the time series get during the 2005 run at Tenerife is exposed in Sect. 6. Section 8 is devoted to conclusions and prospectives.

2. Observations

Observations were conducted at Teide observatory (Canaries islands), with the 1.52-m Carlos Sanchez telescope, between march 31st and April 10th 2005. As it has been detailed in paper I, four images of Jupiter come out from the instrument. Optical parameters inside SYMPA’s box are arranged such as the four 1.3-arcmin fields, cover 128 pixels on the receptor (a DTA CCD, 1024×256 pixels). During the run, Jupiter at opposition presented a diameter of 48 arcsce, corresponding to 69 pixels on the CCD camera.

Seven nights over ten days benefited of good weather conditions, yielding to a 21% duty cycle. Data quality was almost constant from one night to another, excepted for night 2 and 8, where clouds have reduced the incident flux. Observation conditions are summarized in Fig. 1 and Table 1. The window function associated to the whole campaign was very strong, since we consider only Canaries data. Therefore, in the power spectrum, the amplitude of a single spike has been divided by a factor 4, since its power gets diluted in high side lobes (Fig. 2). The total flux was expected to be about 2.4 $10^9$ photons per 6-s exposure (paper I). However, its mean value along the run is about 2.2 $10^3$ photons per exposure (Fig. 1). This discrepancy with the estimated flux introduces a factor 0.95 in the ratio to noise value. In paper I, a noise level of about 4 cm $s^{-1}$ was expected for a 16-nights observation campaign, with 50% duty cycle. Instead of such a performance, by considering only Canaries data, the noise level is therefore expected at 10 cm $s^{-1}$.

3. Data processing strategy

3.1. Four interferograms in phase quadrature

SYMPA’s instrumental principles are fully explained in paper I and are summarized in Fig. 4. The four output beams can be described in the detector coordinates $(x, y)$ by the following approximations:

$$I_1(x, y) = \frac{I_0(x, y)}{4} \left[1 - \gamma \cos \phi(x, y)\right]$$  \hspace{1cm} (1)

$$I_2(x, y) = \frac{I_0(x, y)}{4} \left[1 - \gamma \sin \phi(x, y)\right]$$  \hspace{1cm} (2)

$$I_3(x, y) = \frac{I_0(x, y)}{4} \left[1 + \gamma \cos \phi(x, y)\right]$$  \hspace{1cm} (3)

$$I_4(x, y) = \frac{I_0(x, y)}{4} \left[1 + \gamma \sin \phi(x, y)\right]$$  \hspace{1cm} (4)

where $I_0$ is the continuum component of the incident light, that is to say the Jovian figure, $\gamma$ the fringe contrast and $\phi(x, y)$ the incident wave phase map:

$$\phi(x, y) = 2\pi \sigma_0 \Delta(x, y) \left(1 + \frac{v_D}{c}\right)$$  \hspace{1cm} (5)

where $\sigma_0$ is the central wavenumber of the input filter, $\Delta(x, y)$ is the optical path difference (OPD) and $v_D$ and $c$ are the Doppler and the light velocities. The Doppler shift of the solar Mg lines comes from the combination of the relative motion of Jupiter to the Sun $v_{J/S}$, relative motion of the observer to Jupiter $v_{E/J} + v_{E,rot}$ (distance between the two planets and Earth’s rotation), Jupiter’s rotation $v_{J,rot}$ and, finally, the oscillations $v_{osc}$. In the following, we write the Doppler velocity as the sum of:

$$v_D = 2 \left(v_{J/S} + v_{E/J} + v_{E,rot} + v_{J,rot} + v_{osc}\right)$$  \hspace{1cm} (6)

The factor 2 is due to the fact that the Doppler effect gets doubled after reflection on Jupiter’s atmosphere. The orders
Table 1. 2005 run at Teide Observatory

| Starting date | Ending date | Duration | Mean sampling | Number of acquisitions | Mean Intensity photons image$^{-1}$ | Standard deviation photons image$^{-1}$ |
|---------------|-------------|----------|---------------|------------------------|--------------------------------------|----------------------------------------|
| Apr-02, 23:48:14 | Apr-03, 07:03:40 | 7:09:35 | 5.45 | 4727 | 1.89 $10^9$ | 0.67 $10^9$ |
| Apr-03, 23:30:14 | Apr-04, 07:02:29 | 7:31:59 | 7.13 | 3792 | 1.79 $10^9$ | 5.27 $10^9$ |
| Apr-04, 23:16:12 | Apr-05, 06:58:17 | 7:39:30 | 6.75 | 4080 | 2.50 $10^9$ | 0.76 $10^9$ |
| Apr-05, 23:25:29 | Apr-06, 06:50:23 | 7:22:12 | 6.68 | 3971 | 2.44 $10^9$ | 3.80 $10^9$ |
| Apr-09, 23:20:17 | Apr-10, 06:31:59 | 6:37:48 | 6.28 | 3799 | 2.06 $10^9$ | 3.62 $10^9$ |
| Apr-10, 22:51:11 | Apr-11, 06:33:11 | 7:41:48 | 6.33 | 4376 | 2.38 $10^9$ | 1.14 $10^9$ |
| Apr-11, 21:09:35 | Apr-12, 06:30:17 | 7:20:42 | 6.83 | 3872 | 2.36 $10^9$ | 0.97 $10^9$ |

3.2. Extracting the oscillation signal

Let us consider a quadruplet of interfering images on the detector’s field. The differences between the two couples of images, which are in phase opposition, allow to cancel the continuous component of the interferograms $I_0$, in order to keep the interfering patterns. We write $U$ and $V$ the normalized interfering patterns:

$$U = \frac{I_1 - I_3}{I_1 + I_3} \propto \gamma \cos \phi$$

$$V = \frac{I_2 - I_4}{I_2 + I_4} \propto \gamma \sin \phi$$

where we let go of $(x, y)$ dependence in order to simplify notations. The incident wave phase is retrieved by taking the argument of the complex interferogram:

$$Z = U + iV \propto \gamma e^{i\phi}$$

The data processing expands in three main steps: correction of the motionless fringes, elimination of Jupiter rotation and elimination of the relative motion of the observer to the target and of the target to the Sun. Mathematically, it lies in creating successively four complex interferograms, associated to each step of the data processing: $Z_0$ for motionless fringes, $Z_{J,rot}$ and $Z_{E,rot}$ for Jupiter’s and Earth’s rotation, $Z_{J,E/J}$ for the relative motion of the Earth to Jupiter and $Z_{J/S}$ for Jupiter’s motion with respect to the Sun. Then, the rough Jupiter complex interferogram $Z_{jup}$ comes deconvoluted from additive signals:

$$Z_{j,flat} = Z_{jup} \times Z_0^* \times Z_{J,rot}^* Z_{E,rot}^* Z_{J/E/J}^* Z_{J/S}$$

$$\propto \exp \left(4\pi \sigma_0 \Delta v_{osc} \right)$$

where the asterisk indicates the complex conjugation. The resulting interferogram is so-called $Z_{j,flat}$ because of the appearance of its argument, i.e. the velocity map. Indeed, since oscillation amplitude is expected to be lower than 0.6 m s$^{-1}$, it is absolutely impossible to see directly oscillation modes in a single phase map, where mean noise level is expected to be about 900 m s$^{-1}$ per pixel (Paper I). Oscillations might be picked out only in the spectrum of long time series.

Table 2. Orders of magnitude of different Doppler shifts during the 2005 run at Teide Observatory.

| Source                  | Velocity (m s$^{-1}$) |
|------------------------|-----------------------|
| Jupiter-Sun            | 0.4                   |
| Jupiter-Earth          | 3142                  |
| Earth rotation         | [−409, 409]           |
| Jupiter rotation       | [−12570, 12570]       |
| Oscillations           | < 0.6                 |

Fig. 3. Schematic view of the SYMPA instrument. The incident light coming from the 1.5-m telescope, passes through a 120-mm collimator and the 5 nm bandwidth interference filter. The optical path difference $\Delta$ occurs inside the Mach-Zehnder prism; it is a function of the heights $H$ and $h$, refraction index $N$ and $n$ and incidence angles into the prism $I$ and $i : \Delta = 2(HN \cos I - hn \cos i)$. The wollaston polarizer separates each output from the interferometric device into two separated beams. In total, the instrument produces on the camera four images of the same field, separated by $\pi/2$ in phase (see paper I).
Fig. 4. Simulation of interferograms along the data processing chain. Top: motionless interferograms ($U_0, V_0$). Middle: Jovian interferogram ($U_{jup}, V_{jup}$) when Jupiter is inclined of −72° with respect to vertical. The interference pattern is mainly due to the coupling between motionless fringes and Jovian rotation (Eq. 6). Bottom: Jovian interferograms deconvoluted from motionless contribution, ($U_{rot}, V_{rot}$), i.e. fringe pattern associated to Jovian rotation. Note that fringes associated to solid rotation present velocity iso-values parallel to the rotation axis. Differential wind profile has not been introduced.

to know Jupiter’s position better than $1/20$ th of pixel. Figure 4 presents simulations of the motionless interferograms, Jovian interferograms and Jovian rotation interferogram.

4. Data calibration

4.1. Pre-processing operations

Pre-processing consists in cleaning each quadruplet of Jovian image ($I_1, I_2, I_3, I_4$) in order to create couples of interferograms ($U, V$). This implies three main operations. First, the camera dark current contribution has to be subtracted, by using offset images. Second, the inhomogeneities of the single pixel responses to light intensity (photon/electron gain) have to be compensated by dividing each image by a flat field image. Third, the construction of the Jupiter phase map, using the argument of the complex image created by the difference of two couples of images, requires that all the four images overlap one to each other.

Fig. 5. Overlapping of grids 1 and 3, before then after distortion rectification. The position of the horizontal and vertical lines are determined by fitting the zeros of the grid image derivatives, along both directions $x$ and $y$. Second order polynomials are sufficient, since rotation and barrel distortion do not require higher orders. Then, each intersection point coordinates are calculated by solving numerically the four order equation coming from the combination of the vertical and the horizontal line fits. The mean distance between intersections points is equal to $5.32 \% \text{pixel}^{-1}$

If the two first points are easy to realize, the last one is pretty delicate because of the required accuracy of about $1/20$ pixel.

As for every optical system including lenses and prisms, field distortion is unavoidable. Although Jupiter was positioned as close as possible to the optical axis, its large diameter involves differential distortions between the four images, making the overlapping impossible. The whole distortion effect is supposed to be composed of only translation, rotation and barrel distortion. This problem has been anticipated by putting a regular grid, engraved on a glass slice, at the instrument focus. The grid intersection positions are used to characterize the distortion (Fig. 5).

Let us consider one image among the quadruplet $I_i(x, y)$, $i \in [1, 4]$, where $(x, y)$ are the detector coordinates (CCD pixels). Because of optical distortion, the image value on the $(x_k, y_k)$ point, $k \in [1, 128]$, actually corresponds to the $(x'_k, y'_k)$ point. The repositioning algorithm must produce for each image $I_i$ an image $I'_i$, defined in the detector’s coordinates, as:

$$I'_i(x, y) = I_i(x', y')$$

The distorted coordinates $(x', y')$ are related to the regular detector coordinates by the relations:

$$x' = x + f(x, y) \quad \text{and} \quad y' = y + g(x, y)$$

where $f$ and $g$ are polynomials expressed as $\sum_k C_k x^j y^{k-j}$, where $k$ is the polynomial order and $j \leq k$. The polynomial coefficients $C_k$ are obtained by minimizing the difference between the intersection point coordinates of the grid associated to the considered image $I_i$ and the intersection point coordinates of the regular grid. The knowledge of the set of distorted coordinates $(x', y')$ is used to build the new rectified image $I'_i(x, y)$, by interpolation of $I_i(x', y')$ upon the regular detector coordinates.

Interpolation is realized with cubic method. In Fig. 5 we present a couple of 2-grid images before and after repositioning. Note that the translation repositioning represents the zero order of the transformation. A way to evaluate the accuracy of the repositioning process is to apply it to the previously repositioned grids; they should overlap (Fig.
right). The mean distance between the repositioned intersection points from one grid to another belongs to the range [1/20, 1/15] pixel, which almost fulfills the required accuracy.

In order to respect the conservation of the flux, correcting operations have to be processed in the following order: first, subtraction of the offset to the image and to the flat-field, then rectification of the offset-corrected image and flat-field.

\[ I_{\text{processed}} = \frac{[I(x, y, T) - O(x, y, T)]_{\text{rectified}}}{[F(x, y, T) - O(x, y, T)]_{\text{rectified}}} \]  

(14)

where \( I \) indicates the considered image (e.g. Jupiter), \( O \) the offset image and \( F \) the flat-field image. \( T \) stands for the temperature of the camera. Note that assessing the four output intensities are not strictly equal, no photometric balance has to be performed since it is implicitly done by dividing each image by the flat field.

### 4.2. Motionless fringes calibration

The next step of data processing is the deconvolution of Jovian complex interferograms \( Z_{\text{jup}} \) from motionless interferogram \( Z_0 \). Therefore, we have to characterize the motionless phase term \( 2\pi \sigma_0 \Delta(x, y) \) (Eqt. 3). Furthermore, as it has been reported in paper I, the four output beams are not in perfect phase quadrature: the discrepancies between actual measurements and theoretical expectation are about \( \varepsilon = 28^\circ \). This shift compared to quadrature has to be quantified precisely across the whole field \((x, y)\).

The knowledge of the optical parameters of both telescope and instrument permits to describe the motionless fringes (cf simulations on Fig. 4), but not their imperfections. Strong constraints on the motionless fringes come from solar light scattered by the telescope dome. Indeed, excluding the spectral Doppler shift, it presents the same spectrum as Jupiter, since 517-nm magnesium lines are solar reflected lines. Moreover such a process enables to enlighten all the detector surface. Actually, the only difference between motionless fringes and “sky” fringes is the uniform velocity field, introduced mainly by Earth rotation, much less by Sun-Earth distance variation and by undesired thermal effects (see Sect. 6). These parameters are taken into account thanks to the IMCCE ephemeride data base (www.imcce.fr).

6-hour long “sky” shots were taken on April 2nd. In order to increase the signal to noise ratio of sky interferograms, images are averaged over one minute intervals, which corresponds to three images. Figure 6 presents one of the 330 couples of 1-minute exposure interferograms. Fringes are well defined and fringe contrast (\( \approx 0.4\% \)) is smaller than expected (0.8 %). Unfortunately, it appears that the map of both interferograms are not plane, but smaller than expected (0.8 %). Unfortunately, it appears that the map of both interferograms are not plane, but unflatness terms and brings to the two interfering patterns:

\[ \Delta U = U' - U = -\gamma U \left[ 2 \sin \left( \frac{\delta \phi}{2} \right) \right] \sin(\varphi) \]

(17)

\[ \Delta V = V' - V = \gamma V \left[ 2 \sin \left( \frac{\delta \phi}{2} \right) \right] \cos(\varphi + \varepsilon) \]  

(18)

where \( \varphi \) is the mean phase \( \varphi = \phi + \delta \phi/2 \). Figure 7 shows cuts of \( (\Delta U, \Delta V) \) along the x-axis; the unflatness problem has been corrected. The fringe contrast presents optimized variations across both fields, from 0.2% to 0.6%.

The motionless complex interferograms \( Z_0 = U_0 + iV_0 \) is obtained by fitting both quadrature shift and phase on
the couple $(\Delta U, \Delta V)$. First, the plot of one of the interference pattern as a function of the other highlights the phase quadrature imperfections (Fig. 8). In case of perfect quadrature and uniform contrast in both interferograms, points would be distributed around a circle centered on 0. As a result, points are distributed along an ellipse, whose radius varies strongly on detector field. The phase shift $\varepsilon$ with respect to quadrature is related to the ellipse parameters $(A, B)$ by:

$$\varepsilon = \arcsin \left( \frac{A^2 - B^2}{A^2 + B^2} \right)$$

(19)

Since ellipticity and amplitude vary across the field (Fig. 8 left), a further correction has to be applied. Therefore, the field $(x, y)$ is divided in 10-pixel large squares, in which all these parameters are considered as uniform. Ellipse axis are estimated by least square fitting. The resulting parameters estimate $(A, B)$, obtained for each sub-region, are interpolated for each pixel, by fitting their values by a 4th order polynomial. Thereafter, thanks to $A$, $B$ and $\varepsilon$, the amplitude of both interference patterns $(\Delta U, \Delta V)$ is normalized to 1 and the phase shift is set to 90°, by the operation:

$$\Delta U' = \frac{\Delta U_{\text{norm}} \cos(\varepsilon/2) - \Delta V_{\text{norm}} \sin(\varepsilon/2)}{\cos(\varepsilon/2)}$$

(20)

$$\Delta V' = \frac{\Delta V_{\text{norm}} \cos(\varepsilon/2) - \Delta U_{\text{norm}} \sin(\varepsilon/2)}{\cos(\varepsilon/2)}$$

(21)

where the subscript “norm” indicates that amplitudes have been normalized to 1. These new variables are now in the required quadrature. Figure 8 shows the plot of the interference pattern $U$ as a function of the other $V$; phase quadrature is reached. At last, the motionless phase $\phi_{\text{instr}}$ is obtained by fitting with a 4th order polynomial the argument of the complex interferogram $Z_{\text{sky}} = \Delta U' + i\Delta V'$. The resulting phase standard deviation is about 5.3°.

The motionless interferogram used in the following to process Jovian data is simply built as:

$$Z_0 = e^{i\phi_{\text{instr}}}$$

(22)

Indeed, since only the phase term matters, the fringe contrast is set equal to 1 in the whole field.

5. From four Jupiter images to a velocity map

Processing the data lies in turning each quadruplet of Jovian images into a calibrated radial velocity map. The first step, developed in the previous section, gives clean fringes on both interference patterns $(U_{\text{jup}}, V_{\text{jup}})$, in order to create the complex Jovian interferogram $Z_{\text{jup}}$. Second, motionless phase is deconvoluted to $Z_0$ with the help of $Z_0$ (Eq. 22). Third, Jovian rotation and other uniform velocity drifts have to be deconvoluted, in order to extract the velocity map.

5.1. Cleaning Jovian fringes

Let us consider a quadruplet of 4 pre-processed Jovian images. Since they have been corrected from flat field and optical distortions, each couple of images $(I_1, I_3)$ and $(I_2, I_4)$ present the same intensity level and shall overlap (Fig. 9). Then, the two interfering patterns $(U_{\text{jup}}, V_{\text{jup}})$ are created following Eqs. 7 and 8. Moreover, they are set in phase quadrature following relation (20) and (21). As it can be seen in Figs. 11 interfere fringes appear, but, as for the “sky” interferograms, the fringes do not oscillate around 0, but around a distorted surface. These features are photometric residues, which have not disappeared with operations (7) and (8). However, fringes have to be repositioned around a flat surface, centered around 0, in order to follow the phase of the Doppler signal.

The best way to separate the photometric noise and spurious signal resides in filtering in the spatial frequency domain. The two dimension fast Fourier transform (FFT) is applied to the complex interferogram $Z_{\text{jup}}$. In order to avoid spectral leakage due to the finite size of the image, we apply an oversampling on the data $Z_{\text{jup}}$, by a factor 2, before passing to the Fourier domain. Besides, Jupiter’s boundary is apodized with a $\cos^3$ function, to avoid Airy-like re-bounds due to Fourier transform. In Fig. 11 we present the Fourier transform modulus. The central region contains the low frequency information (mean value, slow distortions). The horizontal line corresponds to the interference pattern; the horizontal structure comes from the fact that optical path difference varies essentially with $x$-coordinates. The inclined alignment of stains constitutes the photometric ef-
fect. Indeed, it corresponds to the spatial frequencies along the rotation axis of Jupiter, which is inclined of about $-72^\circ$ in the detector’s field. These features are actually remnants of cloud zones and belts.

Wiener filtering stipulates that signal can be filtered out from noise in the Fourier domain if they were clearly differentiable. As it can be seen in Fig. 11 fringes occupy distinct positions from photometric residues. Actually, for high degree modes, a coupling between photometric noise and oscillation signal still exists, since high degree spherical harmonics extend largely in the Fourier domain. Therefore, part of the energy in the largest spatial frequencies may be filtered during this operation. Nevertheless, higher frequency mode information will be still available, since most of its signal is not cancelled by filtering operations, but may suffer from amplitude estimate uncertainty.

In order to limit the damage generated by filtering the noise, the spatial filter is as smooth as possible. It consists of an ellipse, which major axis inclined of $-72^\circ$ with respect to vertical, which includes only the photometric stains and the central region. Besides, as for Jupiter, filter’s boundary is apodized to avoid rebounds by applying the inverse Fourier transform, when getting back to the image plane. The resulting couple of interference patterns, after spatial filtering is presented in Fig. 11. Now, fringes are centered around the 0 value. Hence, requirements for deconvoluting the motionless phase are achieved.

5.2. Jupiter velocity map

The motionless fringe deconvolution is realized by the following operation:

$$Z_{j,\text{rot}} = Z_{\text{jup}} \times Z_0$$  \hspace{1cm} (23)

The resulting interference pattern presents fringes parallel to the planetary rotation axis (Fig. 13). Indeed, the projection of Jupiter’s velocity field $v = \Omega R(L)$, where $\Omega$ is the angular velocity and $L$ the latitude, towards the observer reduces to $v = \Omega x$, where $x$ is the abscissa along Jupiter’s equator. At zero order, Jovian rotation can be considered as solid rotation since differential rotation with respect to solid-body rotation is about 1% on the equator. Thus, $\Omega$ is almost uniform on the Jovian disk, and the phase of the complex interferogram presents iso-values along the rotation axis. Moreover, note that since noise level is about 900 ms$^{-1}$ per pixel, differential rotation is definitely invisible on a single image.

Hence, a complex phaser which reproduces the solid rotation is applied to each Jovian complex interferogram; it is defined by $Z_{\text{solidrot}} = \exp(4\pi\sigma\Delta v_{\text{rot}}/c)$, where $v_{\text{rot}} = 2\pi/T$ and where $T = 9$ h 55 m 30 s (system III) is the mean rotation period. The main difficulty of such a process lays on the accuracy of the estimate of Jupiter’s position on the detector, because 1 pixel corresponds to 350 ms$^{-1}$. Two methods have been envisioned to make the center of the solid rotation phaser $Z_{\text{solidrot}}$ overlap on the center of Jupiter’s
interferogram $Z_{j, \text{rot}}$. In both cases, a threshold is applied to each image, in order to get rid of spurious photometric signals, such as Jovian satellites of terrestrial atmospheric light scattering. The “barycenter” method consists in taking the coordinates of the barycenter of the total photometric image $I = \sum_{i=1}^{4} I_i$. The “interspectrum” method consists in determining the relative distance between two images, taken at different dates, by measuring the phase \( \Phi \) of the interspectrum of the two images. Indeed, the phase of the interspectrum of the couple of images \((I_1, I_2)\) is defined as:

\[
\Phi = \arg \left\{ \mathcal{F}(I_1) \times \mathcal{F}(I_2)^* \right\}
\]

(24)

\[
\propto (x_2 - x_1) + (y_2 - y_1)
\]

(25)

where \((x_1, y_1)\) and \((x_2, y_2)\) are the coordinates of the center of Jupiter and \(\mathcal{F}\) and \(\mathcal{F}^*\) indicate the Fourier and inverse Fourier transformations. The second method has been preferred because the barycenter estimate is too sensitive to high spatial frequency photometric details, which vary along the night, as cloud features or satellite transits. On the contrary, the interspectrum method is sensitive only to low spatial frequency.

After deconvolution of Jovian mean rotation (i.e. solid body approximation), interferograms become flat since the remaining phase \( \phi = 4\pi \sigma (v_{1/8} + v_{E/1} + v_{E, \text{rot}} + v_{\text{sec}}) \) is uniform across the field (Fig. 14). The subtraction of \( v_{1/8} \) and \( v_{E/1} \) is exposed in the next section, since they do not change the noise to signal ratio of the phase map. Therefore, the velocity map is retrieved thank to Eq. 6 in paper I:

\[
v = v_0 \arg \{ Z_{\text{flat}} \}
\]

(26)

with \( v_0 \approx 1 \text{ km s}^{-1} \). Note that because of apodization created by spatial filtering of photometric residuals, the entire phase map is not exploitable. A part of the external region is cut down, whose proportion is a function of the apodization strength. Here, an external ring representing 1/4 of the Jovian radius is taken away (Fig. 14). As a consequence, the flux is reduced by about of the partial elimination of Jupiter’s is the loss of 43 % of the photons, which make the expected noise level go up around 10.5 cm s\(^{-1}\). However, the performance decrease is limited by the low weight of external regions in the Doppler signal.

The standard deviation of velocity across the Jovian disk is about 890 ms\(^{-1}\) per pixel, that is to say 18.9 ms\(^{-1}\) when integrating the 2200 pixel of the resized Jovian disk. This performance matches with expectations. If photon noise is reached, a 7-hour night integration with 6-s sampling yields a noise level as small as 20 cm s\(^{-1}\).

6. Temporal analysis over one night

In the previous section, we have exposed the data processing method for a single Jupiter quadruplet, for the extraction of the Doppler signal. In this section, we analyse the time series of the median phase extracted for each Jovian quadruplet. Then, we identify the different sources of noise and present correction methods.

6.1. Phase global behavior

The study of median phase along a single night allows us to evaluate the mean noise level and to identify spurious signals. Median phases are extracted from Jupiter’s flat interferograms $Z_{\text{flat}}$ as follow:

\[
\phi_{\text{med}} = \arctan \left( \frac{V_{\text{med}}}{U_{\text{med}}} \right)
\]

(27)

where the subscript “med” indicates the median value of the considered variable. This estimate of Jupiter median phase has been preferred to the direct median of the phase map, in order to avoid noise coming from 2\(\pi\) jumps (see Fig. 14). In Fig. 15 median phase along night 9 and its power spectrum have been plotted.

First, according to data processing chain (Eqs. 1, 11 and 12), phase measurement is proportional to the redshift of spectral lines, it appears that the signal is overwhelmed by a strong low frequency noise. Indeed, along the night, the velocity variation should be dominated by the Earth rotation (409 m/s amplitude at Teide observatory), so the phase shall increase of about 0.41 rad instead of decreasing of about 1.12 rad. This implies that an unexpected stronger low frequency drift dominates. Besides this low frequency noise, the power spectrum highlights a rapid oscillation noise source around 6-mHz frequency.

Anyway, the standard deviation of median phase is around 27 m s\(^{-1}\) per image; images were taken every 6 s. By supposing an only photon noise origin, the noise level reduces to 15 cm s\(^{-1}\) for 7 nights of 7 hours, which is 1.3 time worse than expected from previous section. In the following subsections, we interpret the noise origins and describe the method which has been used to get rid of their main effects.

6.2. Temperature effect

Paper I has expose that the interferometer is made of two pieces of two different glasses, specially chosen as to compensate the index variations and the dilatation, in order to have a stable OPD. In particular, a temperature variation of about 1°C should have no effect on OPD in 14°C environment.

The median of Jupiter’s median phase over each night has been plotted as a function of the corresponding me-
Median temperature (Fig. 16). Phase and temperature appear clearly correlated. A variation of 1°C introduces a phase shift of 0.33 rad (i.e. 330 m s\(^{-1}\)), which is much above than expected (between −60 m s\(^{-1}\) and 30 m s\(^{-1}\) for temperature between 0 and 20°C; see paper I). In fact, such a thermal effect is retrieved when taking into account the error bars upon dilatation coefficient and refractive index thermal dependance (±10%).

Unfortunately, the correlation coefficient reported in Fig. 16 does not allow us to correct Jovian phase map from its thermal dependence. Indeed, the comparison of phase and temperature over one night does not match correctly: a several hour delay is still present (Fig. 17). This discrepancy is due to the fact that temperature measurements do not correspond to the Mach-Zehnder prism, but to the metallic box which holds it on. Because of a greater thermal inertia, glass actual temperature is time-shifted with respect to metal temperature. Therefore, a low frequency filter is applied to data in order to reduce the noise in the frequency range below 0.2 mHz.

Beyond a mean OPD drift, temperature variations generate differential OPD variations with respect to light incidence angle onto the prism. Since Jovian interferograms get deconvoluted from motionless fringes with the help of a constant interferogram (Eq. 23), the differential OPD variations introduce a slowly varying inclined surface in Jovian flat phase maps (Fig. 18). This surface is bent along the x-axis because OPD is only x-dependent. Such an inclined surface yields a high frequency perturbation correlated to Jupiter’s position in the observed field. This noise is reduced by fitting the spurious surface on each phase map, by a plane inclined only with respect to x-axis. Thereafter, Jupiter’s phase map are set flat by using a smoothed estimate of the fitted parameters.

6.3. Guiding noise

The so-called “guiding noise” is the perturbation related to Jupiter’s position, which should not occur if Jupiter were at fixed position. Theoretically, SYMPA’s Doppler velocity measurements are not sensitive to Jupiter’s position onto the field, because after motionless fringe deconvolution (Eq. 23) nothing should depend on the coordinates. However, the comparison between spectra of
I−to decorrelate only significant guiding noise spikes. Note that we apply a 75% threshold upon I and to 12 cm s−1 noise is ignored. The noise level reduces to 32-cm s−1 by supposing the remaining noise is only due to photons,−1 where φ is defined by:

\[ I_x = \frac{2}{\pi} \arcsin \left( \frac{\mathbb{R}\{F(\phi)F^*(x)\}}{|F(\phi)| |F^*(x)|} \right) \]

\[ I_y = \frac{2}{\pi} \arcsin \left( \frac{\mathbb{R}\{F(\phi_{\text{decorr}/x})F^*(x)\}}{|F(\phi_{\text{decorr}/x})| |F^*(x)|} \right) \]

Note that we apply a 75% threshold upon \( I_x \) and \( I_y \) in order to decorrelate only significant guiding noise spikes.

Jupiter’s phase standard deviation drops down from 27 m s−1 per image to 21 m s−1, which is very close to the expected photon noise level (19 m s−1 per image). Hence, by supposing the remaining noise is only due to photons, the noise level reduces to 32-cm s−1 on a 7-hour integration and to 12 cm s−1 after 7 nights. The remaining not-photon noise is ignored.

Fig. 19. Top. Jupiter’s coordinates \((x, y)\) in the CCD field over night 9. Note that \( y \) varies much more than \( x \) coordinate because Jupiter is rotated about −72° on the image and because most of the telescope guiding problems occur with the right ascension. Bottom. Amplitude spectrum of both coordinates. They present strong components below 6 mHz and significative spikes up to 18 mHz.

### 7. The search for oscillations: no evidence for a Jovian signal

#### 7.1. Decomposition into spherical harmonic base

A stationary oscillation mode can be described as the sum of two spherical harmonics of degree \( \ell \) and order \( \pm m \). Jupiter velocity field related to \( \rho \)-modes follows such a description. Therefore, the Doppler signature of the radial velocity field expands in a base made of the projected complex spherical harmonics towards the observer.

The coefficients \( c_{\ell m} \) associated to each spherical harmonics \( Y_{\ell m} \) are obtained as follow:

\[ c_{\ell m} = \frac{\sum_{\text{pixels}} \mathbb{R}\{Y_{\ell m}\} \times I}{\sum_{\text{pixels}} |Y_{\ell m}|} + \frac{\sum_{\text{pixels}} \mathbb{I}\{Y_{\ell m}\} \times I}{\sum_{\text{pixels}} |Y_{\ell m}|} \]

where \( I \) indicates the velocity map (Eqt. 20). The normalisation coefficient is done with respect to the actual number of pixel after resizing. The \( c_{\ell m} \) coefficient modulus are expressed in m s−1. Oscillation search is performed in the spectra of all spherical harmonics up to the degree \( \ell = 25 \).

#### 7.2. Regular temporal grid

Velocity maps are extracted from mean flat interferograms, averaged within 30-s intervals, but calculated every 15 s. Such a process has two reasons. On one hand, the mean noise level inside velocity maps drops down of a factor \( \sqrt{5} \) since 30 s contains 5 images, which limits strongly the 2π jumps which appear when applying Eqt. 20. On the other hand, it allows to use the fast Fourier transform (FFT) to calculate the power spectra. The procedure is of great interest because the search for modes up to 25 means 625 spectra of 27000 point in the time series. The spacing of data every 15 s imposes a cut-off frequency at 16.3 mHz, which is well beyond the expected p-modes (less than 3.5 mHz from Mosser 1995). The averaging within 30-s intervals is done in order to avoid spectrum leakage when calculating the Fourier transform.

#### 7.3. Power spectrum of modes (\( \ell = 0, m = 0 \)) and (\( \ell = 1, m = 0 \))

We present the power spectrum of the time series corresponding to spherical harmonics \( Y_0^0 \) and \( Y_1^0 \), for all the data of Canaries observation campaign. The choice of these two modes among 625, permits to present the two main types of spectra. The first is sensitive to the remaining guiding noise, whereas the second is much less sensitive. Indeed, since guiding noise is mainly due to right ascension control defects, the mode (\( \ell = 1, m = 0 \)) (hereafter (1,0)) is less sensitive to these problems since north and south Jovian hemisphere compensate (Fig. 20).

Both spectra exhibit a flat noise level in the frequency range [1,8] mHz, excepted around 6 mHz, where a guiding signal subsists. Beyond 8 mHz, the averaging over 30 s cuts-off the signal. Guiding signature is reduced from 4 m s−1 to 1.3 m s−1 after decorrelation processes. The mean noise level is about 12.6 cm s−1 for mode (0,0) and 11 cm s−1 for mode (1,0), which squares with the last-estimated photon noise level. Note that such a performance has never been reached on Jupiter and proves that the instrument and the data processing chain works efficiently.
Fig. 20. Power spectrum of time series related to modes (0,0), top, and (1,0), bottom, after concatenation of data along the whole run. The mean noise level are respectively of about 12.6 cm s\(^{-1}\) and 11 cm s\(^{-1}\), what matches with the last estimate of the photon noise. The 6-mHz guiding spike still is about 1.3 m s\(^{-1}\) for the (0,0) mode, whereas it is only about 0.5 m s\(^{-1}\) for the (1,0) mode.

As regards the comparison to previous observations of S91 and M93 and M00, no excess of power is present between in the [1,2] mHz frequency range. Moreover, no large spacing \(\nu_0\) is highlighted, whose value is estimated around 150 \(\mu\)Hz, and which was detected around 136 and 143 \(\mu\)Hz, respectively, by S91 and M00. Such a dissension with previous observations will be analyzed in detail in a future work.

As regards the excess of power in the frequency range [0.3,0.6] mHz, no indication for a Jovian origin can be furnished at this step of the data analysis. It could be a remaining low frequency noise, related to temperature and position. A global analysis over all the modes up to degree \(\ell = 25\) is required to determine its origin and to highlight global signature as Jovian rotation frequency or \(\nu_0\) frequency.

7.4. Global analysis: no evidence for a Jovian signal

As for helioseismology, simultaneous temporal and spatial frequency analysis may reveal the presence of significant information lost among noisy spectra. In Fig. 21 we present the \((\ell, \nu)\) and \((m, \nu)\) diagrams. In the \((\ell, \nu)\) diagram, the low frequency excess of power, picked out in the (0,0) and (1,0) power spectra, is confirmed for almost all degrees \(\ell\) in the frequency range [0.3, 1] mHz. It does not exhibit an organized structure. Moreover, in comparison with past observations, no signal is distinguishable in the [1,2] mHz range. On the other hand, in the \((m, \nu)\) diagram, the same excess of power appears to be strongly structured. The energy is distributed along 2 main lines, symmetric with respect to abscissa, beginning at 0.5 mHz and ending at 1.2 mHz for \(m = \pm 25\). Moreover, a second couple of lines, almost parallel to the first ones, is still visible between frequency 0.7 and 1.6 mHz. The mean slope of the principal lines is about 28 \(\mu\)Hz, which corresponds to Jovian rotation frequency.

A quick analysis of the \((m, \nu)\) diagram gives some indications. A simple guiding noise origin is excluded, because such a spurious signal contaminates all the eigenmodes at the same frequency, as for the 6 mHz spike (see Fig. 21). Furthermore, guiding noise becomes negligible beyond order \(m = 15\), since its effect compensates when applying high order spherical harmonic filtering to velocity maps. At last, if the slope of about 28 \(\mu\)Hz could be casual, it could indicate a Jovian origin to the observed signal.

Fig. 22. Velocity maps averaged over 5 minutes. A fringe structure, inclined of about Jupiter’s inclination on the detector is still present. The coupling of these feature with the spherical harmonic masks may explain the observed features in the \((m, \nu)\) diagram.
However, the Jovian signal hypothesis may vanish by supposing a coupling between two spurious signals. First, it can be noticed, after summation of velocity maps over 10-min, that a fringe structure still remains, which periodicity fits almost with $m_0 = 16$ (Fig. 22). Second, it can reasonably supposed that photometric signal has not been totally removed after the Fourier filtering step (see Sect. 5.1). Thus, a signal modulated by Jupiter’s rotation probably underlies inside velocity maps. The coupling of these two spurious signals introduces a modulation of the signal by a $\cos(m_0\Phi)$ factor, where $\Phi = \Omega_r t$ comes from the photometric remnants; $\Omega_r = 2\pi\nu_r$ indicates the Jovian rotation frequency. Consequently, when applying the spherical harmonic search algorithm (Eqt. 32), a coupling appears between the $\cos(m_0\Phi)$ modulation of velocity maps and the $\cos(m\Phi)$ associated to $Y_m^\ell$. With this assessment, velocity maps are modulated in the following way:

\[
v = v_D \cos(\Omega_r m_0 t) \cos(\Omega_r m t)
\]

\[
= \frac{v_D}{2} \left\{ \cos[\Omega_{rot}(m_0 + m)t] + \cos[\Omega_{rot}(m_0 - m)t] \right\}
\]

Therefore, a linear dependence $\nu = m \nu_r + C$ appears, where the constant term $C = m_0\nu_r$ is about 450 $\mu$Hz, which matches with the observed origin of the two lines.

8. Conclusion and prospects

8.1. Instrumental performance

The aim of SYMPA instrument was the detection and measurements of acoustic modes on the giant planets of the solar system, with a previously unequalled sensitivity around 4 cm s$^{-1}$. Such a performance was estimated for a 16-day observation campaign with 50% duty cycle (see paper I). By choosing to process only the Canaries data, since the instrument used in San Pedro Martir Observatory presents some defects which make the data more difficult to process, the duty cycle is only 21% over 10 nights. In this case, the noise level is reevaluated at 10 cm s$^{-1}$. By taking into account the lack of photons by a factor 2, underlined in Sect. 2, the 1–σ sensitivity decreases to 12 cm s$^{-1}$. After decorrelation of time series with respect to Jupiter’s position on the detector, outside the low frequency range ($\leq 0.8$ mHz) and the 6-mHz spike, the power spectra are flat and the mean noise level reaches 12 cm s$^{-1}$. Such a noise level is 5 time better than previous observations which were limited around 60 cm s$^{-1}$ (M00).

However, the data processing has highlighted some defects, as the too strong optical path difference dependence to temperature and some difficulties, as the separation between photometric and spectrometric information. The latter make the extraction of Doppler velocity hard to practise. This is mainly due to an insufficient accuracy in rectifying the distortion, particularly about the photometric effect of the distortion (variable PSF upon the detector). This point suggests some instrumental modifications, as the time modulation of OPD in order to modulate the phase of the fringe pattern of about $\pi$. It would allow us to replace the spatial subtraction between interferograms by a time subtraction. Moreover, the spectral information would be emphasized more easily by narrowing the entrance filter, which would affect the global sensitivity. This would increase the fringe contrast.
8.2. Jupiter

Jupiter’s seismological observation of S91, M93 and M00 have all exhibited an excess of power in the frequency range [1, 2] mHz, which matches with the theoretical expectations (e.g. Mosser et al. 1996). Moreover, they did not provide any spatial resolution. If both observation methods (sodium cell and Fourier transform spectrometry at fixed OPD) have presented an excess of power in the same frequency range, the large spacing $\nu_0$ estimate was very noisy and differed quite sensitively with respect to the theoretical value of 153 $\mu$Hz (Gudkova et al. 1995).

Our observations do not present features close to $p$-modes signature: the absence of the large spacing $\nu_0$ in power spectra and $(\ell, \nu)$ diagram is significative. However, it is worth to notice that because of the resizing of Jovian velocity maps, the projected spherical harmonic base becomes a quite degenerated base. Therefore, information from a given mode goes diluted into other mode spectra, which may diminish strongly the $p$-mode signature and the identification of specific related structures. A way of leaving degeneracy has to be developed.

Moreover, Bercovici and Schubert (1987) roughly estimated Jupiter’s oscillation velocity amplitude between a few cm s$^{-1}$ and 1 m s$^{-1}$. Therefore it is not abnormal that oscillations are not enlightened with a 12-cm s$^{-1}$ noise level, with a 21% duty cycle. This reduces the observed amplitude of any oscillations by a factor $(0.2)^{0.5}$. In these conditions, only a 25-cm s$^{-1}$ signal could be detected at $1-\sigma$ level.

8.3. Prospects

SYMPA has demonstrated to work properly, after taking into account its technical defects (temperature dependance, field distortions, difference of intensity between the two polarized outputs, lower sensitivity of the CCD). It has permitted to reach the best remote sensing velocity measurements upon giant planets. Some improvements are to be performed on the existing instrument, as a better thermal insulation and a slightly modified optical design in order to reduce the geometrical distortions. An alternative and more efficient solution is to rebuilt a prism, equipped with an OPD time modulation.

From a most general point of view, this seismometer is a tachometer, which furnishes velocity maps, instead of point to point measures, which is the case of echelle-spectrometers. Thus, it can be used to other kind of observations, such as wind velocity measurements. SYMPA has tested an extra seismological application in November 2007, by participating to a ground-based observation campaign organised in sustain to ESA Venus-Express probe, in order to characterize the lower mesosphere wind velocity.

What future for giant planet seismology is the natural question arising at the end of the first run of the first project entirely dedicated to this topic. The main obstacles to such a kind of measurements are the temporal coverage and the atmospheric turbulences. Temporal coverage introduces a windowing effect which makes the signal amplitude drop down and the deconvolution of noise with respect to signal very hard because of the spreading of information into large frequency ranges. Atmospheric turbulences limit the spatial resolution and, above all, make the planet move in the field, which generates guiding noise. A significant improvement would arise with Antarctic observations: Schmider et al. (2005) showed than a 80% duty cycle can be reached for more than 3 months. However, Jupiter south hemisphere oppositions will last till 2009, and afterwards will not occur before 2018.

The ideal opportunity would come from space measurements aboard an interplanetary spacecraft cruising towards Jupiter. With an optical design similar to SYMPA, a 10-cm entrance pupil observing for 2 months at a mean distance of 0.2 AU to Jupiter would allow to reduce the noise level to few mm s$^{-1}$ and to increase the spatial resolution till degree $\ell = 100$. Such an instrumental concept has been proposed to the European project of mission to Europa and the Jupiter system, Laplace, which participates to the ESA’s Cosmic Vision programme (Blanc et al. 2006). The concept, so-called ECHOES, is derived from the ground based instrument SYMPA and the space helio-seismometer MDI onboard SOHO space Solar observatory (Scherrer et al. 1995). It would produce simultaneously intensity maps of reflected solar light, velocity maps and polarimetric maps of the whole visible surface with a spatial resolution of about 500 km at the surface of Jupiter. Also, such an instrument would be an efficient tool to measure the wind velocity of the upper troposphere and the lower stratosphere. Such a spatial project needs a feasibility study. On one hand, from an instrumental point of view. Are the specific requirements of seismology compatible with the interplanetary probe programme? Is the envisioned method the most adequate to space measurements, or COROT-type photometric measurements (Baglin et al. 1998) should be preferred as suggested by Mosser et al. (2004) and Gaulme & Mosser (2005)? On the other hand, theoretical improvements have to be performed about the modes excitation mechanism, in order to evaluate the amplitudes of the expected oscillations.

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