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# Improvement of Doppler measurements thanks to adaptive optics: the case of JOVIAL+AOC

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## ABSTRACT

The JOVIAL instrument is a Doppler imager, dedicated to the study of atmospheric dynamics at the surface of the planets of the Solar System, and in particular Jupiter and Saturn. The principle of this instrument is fully described in several papers presented at previous SPIE meetings<sup>1-4</sup> (Gonçalves et al, 2016; Soulat et al, 2017; Underwood et al, 2017, Schmider et al; 2020). Recently, we obtained instrumental and astrophysical results, showing the performances of the instrument and for the first time, giving zonal and vertical winds measurements at the surface of Jupiter (Gonçalves et al, 2019, Schmider et al 2024).<sup>5,6</sup> The terrestrial atmospheric turbulence remains a strong limitation for this type of measurements. Indeed, the velocity field at the surface is intricately linked with the photometry through the PSF of the instrument, as the measured Doppler shift is the product of the actual velocity by the intensity and convoluted by the PSF<sup>7</sup> (Civeit et al, 2005). Therefore, the large PSF corresponding to long exposure time causes spurious Doppler shift, affecting the accuracy of the measurements. This problem affects any spectroscopic velocity measurements of resolved objects, but is particularly important in the case of Jupiter, which presents strong photometric variations at its surface coupled with a large gradient of velocity due to the fast rotation. In a recent paper,<sup>6</sup> we show the effect of the PSF and calculate the bias that it introduces. We show the data processing that was used to minimize this effect and recover unbiased measurements.

However, this treatment cannot be fully satisfactory, as the PSF itself always varies with time and its shape is not well known, making illusory any type of deconvolution. A best solution would consist in solving the problem at the beginning, i.e. when the images are formed in the instrument. That is why we developed the Adaptive Optics system AOC (Adaptive Optics at C2PU), placed at the entrance of the instrument, and able to correct the wavefront on a field as large as 1 arcmin, sufficient for Jupiter. This field is much larger than the isoplanetic angle, so the correction is limited to the ground layer up to 1000 m, which contains most of the turbulence. Still, the preliminary results show a nice improvement of the quality of the PSF and, as a consequence, a better accuracy of the measured velocity field.

We will illustrate the results of the AOC on observations of Jupiter realized in November 2023. We present how it could improve the precision of the velocity measurement. We will also present the recent improvements of the AOC system and we finally will talk about new ideas to recover the actual velocity field and improve the precision by using the data coming out of the AO system.

**Keywords:** Interferometric Doppler imager, giant planets asteroseismology, planets atmospheric dynamics, ground-based network

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## 1. INTRODUCTION

Sounding the interior of giant planets, as we do for the Earth, could in principle be achieved by measuring the frequencies of the oscillations at their surface. This has been the goal of many attempts since the early 80s and this is the main objective of the JOVIAL network, consisting in 3 similar instruments placed on 3 telescopes around the Earth to catch the small motions of Jupiter to constraint its structure and its formation scenario. The JOVIAL instrument is based on a Mach-Zehnder interferometer sensitive to the Doppler shift of reflected solar lines at the surface of planets in a bandwidth of 1nm around 520 nm. The principle of this instrument is fully described in several papers presented at previous SPIE meetings.<sup>1-4</sup>

Although the main goal was the search for acoustic oscillations, JOVIAL is also capable of monitoring atmospheric dynamics of gaseous planets. Recently, we obtained new instrumental and astrophysical results, showing the performances of the instrument and for the first time, giving zonal and vertical winds measurements at the surface of Jupiter.<sup>5,6</sup> Not only were we able to record the well-known zonal wind profile, very similar to measurements from cloud-tracking, but we have been able to produce full maps of the 3 components of the wind, something unreachable from other techniques. In this recent papers, we show the effect of the atmospheric turbulence on the measurement, which remains a strong limitation factor. Indeed, the large PSF corresponding to a long exposure (1 mn) degrades the velocity measurement, as for any spectroscopic velocity measurements of resolved objects. It is particularly important in the case of Jupiter, which presents strong photometric variations at its surface coupled with a large gradient of velocity along the equator due to the fast rotation ( $\Delta V_{rot} = 25kms^{-1}$ ). The bias is particularly strong at the edges of the planet and near the main photometric structures like the Great Red Spot (GRS). It can produce spurious velocities of the order of 100 m/s, depending on the size of the PSF (see below). That is why having the best possible PSF is crucial for these measurements.



Figure 1. The Jean Gay building at Calern observatory hosting the C2PU telescopes (left). The eastern 1m telescope "Epsilon". Credit Thomas Petit (right)

In this paper, we will summarize the principle of the JOVIAL instrument and the performance which were achieved in the measurement of atmospheric dynamics on Jupiter, based on previous observations. We will then describes the configuration at Calern observatory, where the JOVIAL instrument was installed with the AOC Adaptive Optics system at one of the C2PU telescopes in the Jean Gay building.

## 2. THE JOVIAL IMAGING VELOCIMETER

JOVIAL is the result of the development of a specific Doppler Spectro Imager (DSI), in view of a space mission. The concept was originally proposed for the JUICE mission. It aims to study the dynamics in the atmosphere of gaseous planets and to detect tiny periodic motions coming from the acoustic oscillations. This section describes the principle and design of the JOVIAL instrument, which was built in three copies, one for each site of the JOVIAL network around the world, allowing almost continuous observations for the measurement of acoustic modes on giant planets.

The DSI prototype was developed at the laboratory and tested on the sky. These tests were successful enough to propose a new instrument in view of ground based observations of Jupiter. The tests of the prototype and the conditions of observations in the frame of the network conducted to a new design of the instrument.<sup>1</sup>

This instrument was successfully installed at the Dunn Solar Telescope in Sunspot (NM, USA) and at Okayama observatory<sup>4</sup> in 2019. Disgracefully, the observations were interrupted in 2020 by the pandemic and in 2022 by a major failure of the dome enclosure at Okayama Observatory. The dome should be repaired by next year to resume the observation program.

## 2.1 Measurement principle

The JOVIAL instrument is an interferometric velocimeter. It produces images of the velocity field of Jupiter or any gaseous planet by measuring the Doppler shift of solar lines reflected at the surface. It is based on a Mach Zehnder design (Fig. 2), providing four output images, where the phase of the superimposed fringes is proportional to the Doppler shift of the spectral lines. The Mach-Zehnder is placed into a vacuum tank in order to avoid pressure and temperature variations of the Optical Path Difference (OPD).

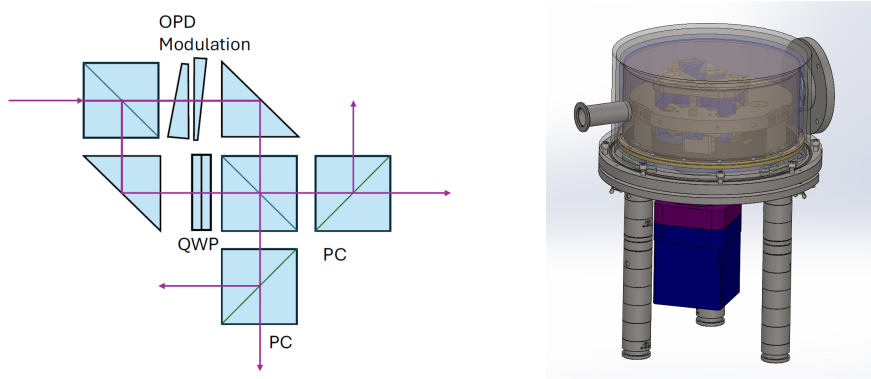


Figure 2. Left: Sketch of the Mach-Zehnder interferometer used for the JOVIAL instrument. On one arm, a QuarterWave Plate introduces a shift between polarizations, on the other one, a modulation of the Optical Path Difference can be done by moving an half plate for calibration purpose. After separation of the polarized beams, the 4 outputs are sent to the detector. Right: The vacuum tank with the MZ and the detector hanging below

### 2.1.1 Equations

The interferometric pattern can be described by the following equation:

$$I(\Delta) = \left| \int S_p(\lambda) \exp \frac{2i\pi\Delta}{\lambda} d\lambda \right|^2 \quad (1)$$

where  $\Delta$  is the Optical Path Difference and  $S_p$  is the entrance spectrum. Here, the bandwidth is limited to 1 nm around 519.6 nm. Due to the presence of several spectral lines (about 10 lines), the output  $I$  has several maxima at large values of the OPD. Around a maximum, the fringes are well described by:

$$I(\Delta) = I_0 \left[ 1 + \gamma \cos \frac{2\pi\Delta(1 + \frac{v}{c})}{\lambda} \right] \quad (2)$$

where  $I_0$  is the mean intensity,  $\gamma$  is the local contrast of the fringes,  $v$  the Doppler shift of the spectral lines, and  $c$  the speed of light. It shows that the phase of the interferometric pattern is proportional to the Doppler shift of the solar spectral lines reflected at the surface of the planet. It has been demonstrated in<sup>8</sup> that the sensitivity to the Doppler shift can be maximized by choosing correctly the bandwidth and the OPD. In our case, we choose an OPD of 5.035 mm for a 1 nm bandwidth at 519.6 nm. This corresponds to a set of solar spectral lines regularly spaced in wavelength. The corresponding theoretical contrast  $\gamma$  is about 5%.

## 2.2 Velocity measurement

As seen in the previous equation, the phase of the fringes is proportional to the Doppler shift. Doppler measurements can be converted into velocity field at the surface of the planet. The total Doppler shift is the sum of the velocity toward the source (the Sun) and the velocity toward the observer, in that case, on the Earth. The different components of the wind, zonal, meridional and vertical, produce different responses on the Doppler signal depending of the projection factors. The projection factors are calculated for the corresponding configuration of the planet, i.e. the direction of the source (the Sun) and the observer. Figure 3 shows the projection factors for an inclination of the planet of 3 degrees and a phase of 4 degrees.

$$v_D = V_E + V_S = f_z V_z + f_m V_m + f_v V_v \quad (3)$$

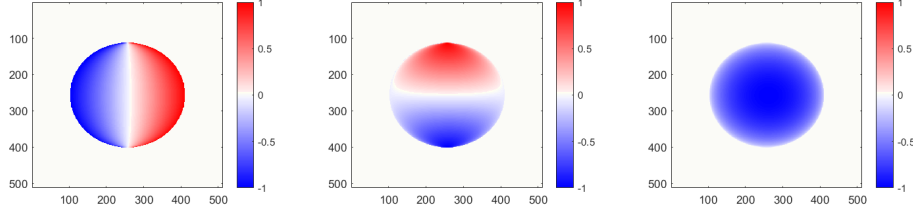


Figure 3. Projection factors of the Doppler shift calculated from the three velocity components zonal  $V_z$  (left), meridional  $V_m$  (middle) and vertical (radial)  $V_v$  (right). Here, the inclination of the planet is 3 degrees and the planetary phase (angle between the Sun and the Earth) is 4 degrees

The JOVIAL project was deployed around the Earth between 2018 and 2021. Th interruption due to the pandemics followed by a major failure of the telescope in Japan has limited our capabilities to get continuous observations of Jupiter as previously thought. However, nice measurements were obtained at the Dunn solar telescope at Sunspot, New Mexico in 2018. The analysis of 12 nights of observations between May 4th and May 31th, 2018, permitted to produce for the first time of zonal and vertical wind maps of Jupiter.<sup>6</sup>

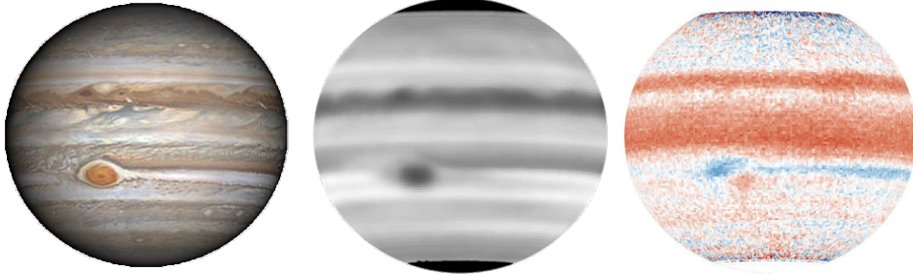


Figure 4. Jupiter as seen with the JOVIAL instrument from the Dunn Solar telescope (middle) and zonal wind obtained in 1 week (right). Left: Image of Jupiter recorded by amateur astronomer Damian Peach at the same epoch than JOVIAL measurement and processed by Peter Rosen

These results required accurate data processing and corrections. Indeed, the velocity field at the surface is mixed with the photometry through the PSF of the instrument, as the measured Doppler velocity  $v_m$  is the product of the actual velocity by the intensity and convoluted by the PSF:<sup>7</sup>

$$v_m = \frac{(F \times v_D) \star P}{F \star P} \quad (4)$$

where  $F$  is the local photometric flux on the planet,  $V_D$  is the actual Doppler shift,  $P$  is the PSF, and the asterisk signs  $\star$  denote the convolution product. The main effect of this integral equation is the existence of a

difference between the actual Doppler shift and the Doppler measurement. This bias could be estimated at first order by computing  $v_m - v_D$  on simulated Jovian’s velocity field. We used for that an high resolution image from HST observations and a zonal wind profile coming from cloud tracking on HST measurements from the HST/OPAL program.<sup>9</sup>

### 2.3 Measurement bias

We calculated the bias induced by the PSF on the Doppler measurement both analytically and on simulations. This allows a correction of the measurements. In particular, we show that the zonal wind is underestimated, with measured winds 20 to 30 m/s lower than actual values in the jets. We can apply a correction based on the model. However, the model assumes a known zonal wind profile and a resolved image of the planet. We show that it is possible to use convoluted images as obtained by JOVIAL to calculate the correction, but it is not perfect and errors of the order of a few m/s remain. This is comparable with the expected vertical winds that we want to measure. That is why it is crucial to have the best possible PSF and to know it perfectly to be able to inverse the equation 4.

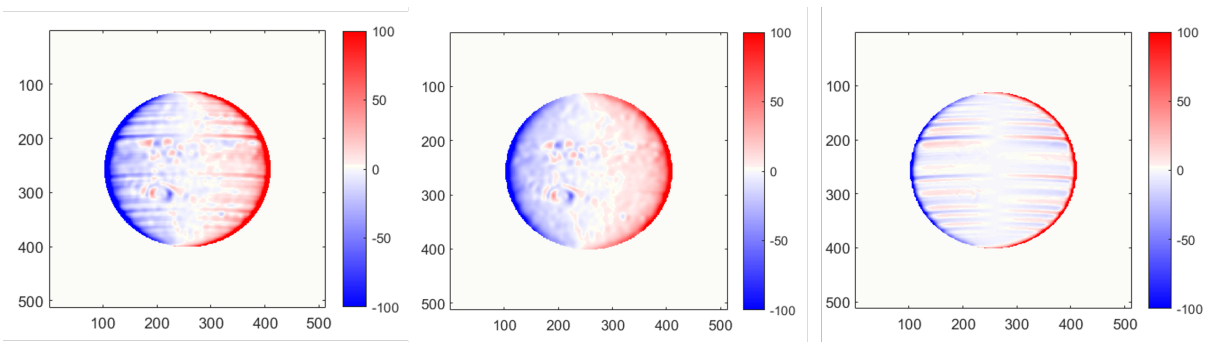


Figure 5. Velocity measurement bias (in m/s) due to the PSF simulated on a resolved image of Jupiter, with a zonal wind model obtained with HST data. The left image show the difference between the actual Doppler shift and the measured one, in the case of a 1.5 arcsec gaussian PSF. Middle: Model of the bias calculated from the convoluted image. Right: Difference between them, showing an underestimation of the zonal wind.

Having an adaptive optics system at the entrance of the JOVIAL instrument will be very useful for these two goals.

## 3. INSTRUMENT CONFIGURATION

The instrument was installed at the 1m telescope Epsilon of C2PU at Calern observatory in December 2020. The whole instrument is placed on a breadboard on a table in the coudé room (Fig. 6 left). The coudé room itself is separated from the telescope dome. The beam is sent along the equatorial axis (Fig. 1) thanks to a M3 mirror placed in the declination axis, and folded by a M4 mirror placed on top of the mount pillar down to the coudé room next to it.

On the optical bench (Fig. 6 right), the beam is sent to the JOVIAL vacuum tank through different optical interfaces including the Adaptive Optics system AOC (Adaptive Optics at Calern). AOC was developed for different applications and progressively improved to be able to provide a corrected wavefront on large objects like planets of the Solar System, and Jupiter in particular. It is also foreseen to be of general use. Different wavelength ranges are separated by several dichroics. The optical bench also includes a Ninox infrared camera and a port for a visible channel. The range between 500 and 600 nm is sent to the JOVIAL instrument.

### 3.1 AOC system configuration

AOC system is based on a Shack-Hartmann wavefront sensor and on a ALPAO DM97 Deformable Mirror. The Shack-Hartmann provides a 10 x 10 subapertures wavefront analysis in a Fried configuration. The first version

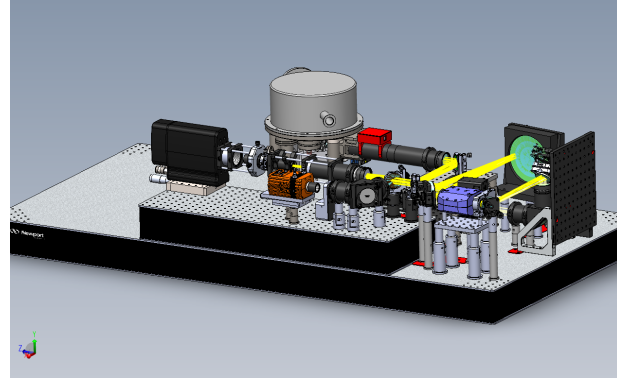
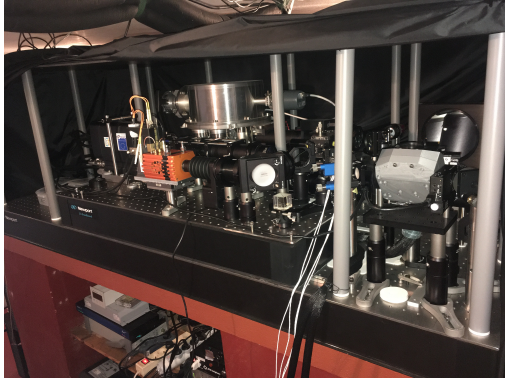


Figure 6. Installation of the JOVIAL instrument at the coude room of the Epsilon telescope with AOC

version was a ANDOR EMCCD Ikon camera with 128x128 pixels and a framerate of 500 Hz. Two fields were provided, one of 8 arcsec for stellar correction, and one of 56 arcsec for planetary observations.

Performances of an AO system are determined by several parameters, such as the number of actuators, the accuracy of the WF measurement, the number of corrected modes, the frequency of the loop. It is also limited by the quality of the system response to wavefront errors. If not well constrained, the control command send to the DM could amplify errors, impacting the quality of the correction, which can even diverge. That is why it is fundamental to precisely define the wavefront reference, corresponding to an expected flat wavefront, and perfectly calculate the interaction matrix between the measured wavefront errors and the mode correction (in case of modal control).

This task could be difficult if it is done on the sky, as the atmospheric turbulence would affect the position of the reference and induce noise in the calibration of the DM response. The AOC system then includes an internal source for calibration and tests. A motorized picking mirror allows to change from the internal source to the beam from the telescope. The internal source includes different source modes. It could be a point source, either with a multimode or a single mode fiber, or a large object with adjustable size up to 60 arcsec, the size of Jupiter. The source itself could be a laser at 633 nm, or a large bandwidth thermal source. The reference source includes a pupil mask similar to the telescope pupil, reproducing the central obstruction. Because of the M3 mirror sending the beam to the coude room, the central obstruction is not circular and its size varies with the declination of the target. Actually, these variations are small for declination between -20 and +20 degrees, which is the useful range for the JOVIAL scientific program. So, the internal source mask is considered to be representative of the telescope pupil. This permits us the calibration of the AOC response on the internal source with enough photons for a very good measurement. The reference position on the Shack-Hartman and the interaction matrix can be used for closing the loop on the sky without change during the night.

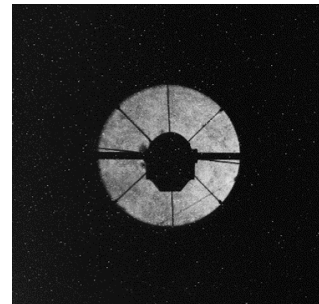
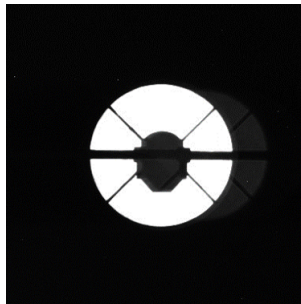
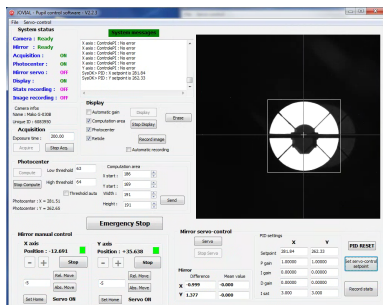


Figure 7. Pupil control system interface (left) and images of the pupil taken by th pupil control camera on the internal source (middle) and on the sky with a star (right).

That's why the AOC system includes a derotator and a pupil stabilization, ensuring a perfect match between

the internal source pupil and the telescope pupil on the sky. The pupil control use a motorized mirror placed at the focus of the telescope and a visible camera on which the pupil is re-imaged. A slow loop corrects the drift of the pupil during the night due to the field rotation.

As explained in Abe et al,<sup>10</sup> Non Common Path Aberrations are calculated from the image in the science channel and added to the reference position obtained with the internal source at the beginning of the observations. This ensures that corrections done on the sky will take into account the telescope aberrations and the optical aberrations between the WFS and the science camera.

In 2024, we improved the system with an OCAM2 240x240 pixels camera, able to reach 1500 Hz in full image and 2.2 kHz in binned mode. Three sets of microlens arrays are now offering fields of 8, 30 and 80 arcsec. Switching between the configurations can be done easily in a few minutes. The loop was tested at 1500Hz. The measured delay of the loop, including image transfer, correction calculation and DM setting time, was of the order of one frame, i.e. 700  $\mu$ s. This can still be optimized. The goal would be to reduced this delay by a factor of 2. In 2x2 binned mode, a framerate of 2.2 kHz could be achieved. With a number of pixels reduced by a factor 4, the computation time should be also reduced to reach this performance.

#### 4. PRELIMINARY RESULTS AND PERFORMANCES

In October 2023, we observed Jupiter with the JOVIAL instrument and a first version of the AOC adaptive Optics system, which was still under development. After a few attempts, we could close the loop on the planet as the target for the Shack-Hartman wave-front sensor. The gain was adjusted as a function of the  $r_0$ . The frequency of the loop was 500 Hz. The weather conditions were awful, with a lot of wind. However, we got a few hours, with average to good conditions. The images were obtained from the auxiliary field camera, with a FOV of 50 arcsec in a bandwidth between 400 and 500 nm and a pixel resolution of 0.1 arcsec.

At this wavelength, the correction could not be excellent. Previous simulations were giving 5% Strehl ratio in good seeing conditions.<sup>11</sup> Here, we don't have an estimate of the Strehl ratio as we do not have any point object in the image. However, we clearly see an improvement of the image quality. Not only the size of the PSF is reduced, but it is also more stable and static aberrations could be corrected. As a consequence, the velocity measurements were less affected by the effect of the PSF. In that case, we did not intent to deconvolve the measurements from the PSF, but this is typically what we would like to do in the future.

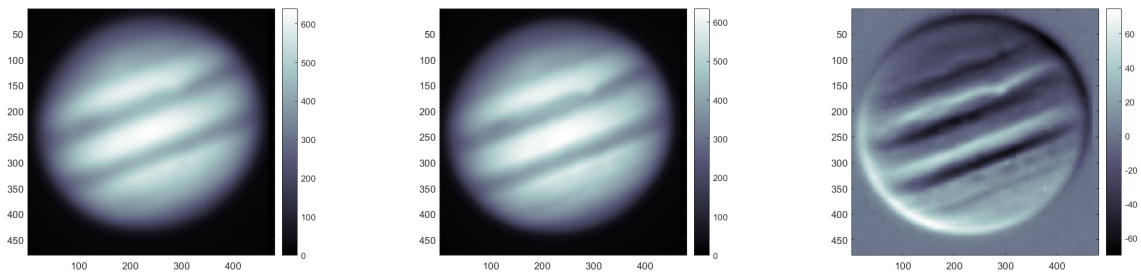


Figure 8. Images of Jupiter of 1 mn exposure time with AO Off (left) and On (middle). Right: the difference between the two. It clearly shows an increase of the contrast in the zones and belts, and much more high resolution details along the latitude

These preliminary results show a significant improvement of the image quality, despite the very preliminary set-up of the AO system. Figure 9 shows a strong increase of the contrast at low spatial frequencies, but only a small increase for high spatial frequencies. This might be due to the averaging of the wavefront measurement on the whole planet in each sub-pupil if the high altitude turbulence layer was strong at that moment, or to the limited performances of the AO loop at that time. In particular the correction was limited to 10 modes at a frequency of 500 Hz. Although no AO data was recorded, the improvement seems coherent with simulations of the AO system previously published.<sup>11</sup> We therefore expect much better results with the new set-up.<sup>10</sup>



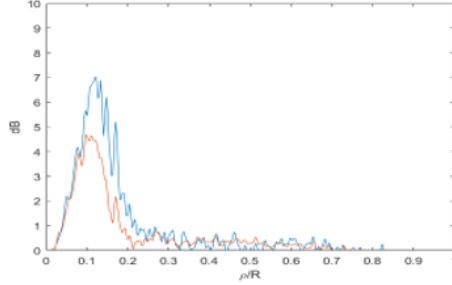


Figure 9. Transfer function calculated as the log-ratio of the Fourier transforms of the Jupiter images with and without AO corrections, displayed as a function of the normalized spatial frequency  $\rho/R$  with  $R$  the radius of the telescope (0.5m). The blue curve is calculated along the Jupiter rotation axis (with the strongest contrast), and the red one along the equator. Both show a strong increase at low spatial frequencies (above 1 arcsec)

We know that the velocity measurement accuracy is mainly dependant of the size and stability of the PSF. With an improvement of the PSF size by a factor of 2, the accuracy of the wind measurements will also improve drastically. With a 1 arcsec PSF, the underestimation of the zonal wind could reach 20 m/s in the jets. Even with a partial correction on a field of 1 arcmin, corresponding to the size of Jupiter, a FWHM lower than 0.5 arcsec is expected. Moreover, the PSF will be more stable and corrected from static aberrations. With a 0.5 arcsec FWHM, the inaccuracy of the wind velocity measurement is always lower than 5 m/s and could be easily corrected by deconvolution. Moreover, the small errors due to the high resolution structures, which could reach up to 5 m/s for a 1.5 arcsec seeing will be reduced to 1 m/s with a corrected PSF of 0.5 arcsec. In these conditions, we will be able to measure precisely vertical and meridional winds which are supposed to be lower than 10 m/s.

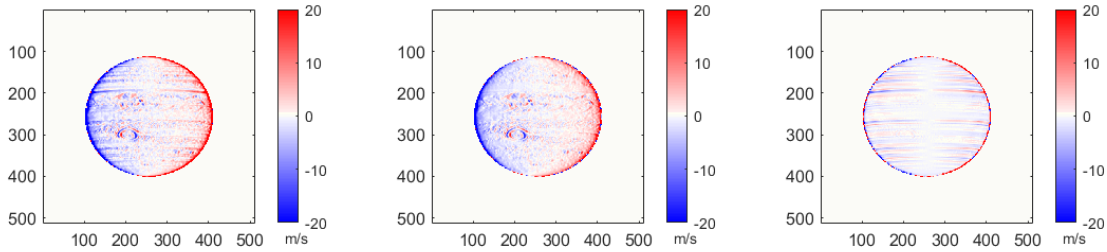


Figure 10. Same as figure 5 with a 0.5 arcsec PSF. Difference between biased velocity measurement and model, showing an underestimation of the zonal wind. Here, the velocity scale (in m/s) is reduced by a factor 5 with respect to the previous figure.

## 5. CONCLUSION AND PERSPECTIVES

In October 2023, we observed Jupiter with the JOVIAL instrument and the Adaptive Optics system AOC at the Calern observatory. Despite adverse meteorological conditions, good measurements were done during one night when the AOC was fully operational. At that occasion, we recorded images with and without Adaptive Optics, showing a significant improvement of the image quality, already permitting a better Doppler shift measurements with the JOVIAL instrument.

In 2024, the WFS was equipped with a new camera OCAM2 able to reach 1500 frames/s with 240x240 pixels against 500 Hz in the previous version. Together with the change of the camera, the Shack-Hartmann design was modified to permit 3 different configurations, giving access to fields of 8, 30 and 80 arcsec. With a 2x2 binning, a frame-rate of 2.2 kHz could be achieved.

Simulations done with CAOS and instant\_GLAO (Abe et al, this proceedings<sup>10</sup>) prove that a partial correction on Jupiter would be achieved, with a Strehl ratio of the order of 10% in the visible domain. This is coherent with previously obtained results and will improve significantly the performances. A zonal modal should also be implemented and tested. It supposes to filter invisible modes in the AO system. We are presently developing this filtering and should be able to test it in autumn 2024. In zonal mode, with the planetary mode, we expect a partial correction providing a limited Strehl ratio in the visible, not better than 10 %, but giving FWHM of the order of 0.5 arcsec.

JOVIAL is foreseen to give 3D wind maps of Jupiter and other gaseous planets, but the measurements are biased by the PSF. The JOVIAL instrument with Adaptive Optics system was installed and tested at Calern observatory on Jupiter. Preliminary results with a first set-up show an improvement of the resolution and stability of the PSF, allowing more accurate wind measurement. The new configuration with a faster WFS should improve the performances of the correction as shown on simulations and permit better wind speed measurements at the surface of planets. One important feature, not yet implemented, is the use of the AO telemetry to calculate the residual wavefront error and estimate the PSF shape. This would be important to deconvolve the image and invert the equation 4.

This mode will be used in particular for observations of Saturn in October 2025, when the Earth will be in the plane of the rings, a configuration which occurs only every 20 years. We will be able to see the whole planet surface and measure detailed winds structure. This would be a unique opportunity to measure the 3D wind field at the surface of Saturn, a completely new achievement.

## ACKNOWLEDGMENTS

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