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ABSTRACT

We describe the performances of a novel Doppler imager, aimed to detect acoustic oscillations and atmospheric dynamics at the surface of giant planets of the Solar System in the frame of the JOVIAL (Jovian Oscillations detection by Velocity Imaging At several Longitudes) project. The first JOVIAL instrument was installed on the 188cm telescope at Okayama branch of National Astronomical Observatory of Japan (NAOJ) in April 2019. This instrument is a part of a ground based network of three identical instruments installed on telescopes around the world for continuous observations. First observations of Jupiter with the JOVIAL instrument were achieved in June 2019. We describe the instrument principle, its design and the set-up at Okayama observatory, as well as the performances reached during the first observing run. We finally provide plans for future observations with the network.

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

1. INTRODUCTION

Understanding the giant planets of our solar system would give clues about the solar system formation and the evolution of giant planets, as compared to exoplanets. Recently, JUNO provided new results, leading to constraints on differential rotation below the visible cloud layers,[1,2] and suggesting that a gradient of heavy elements in the form of a dilute core could be present in the deep interior.[3–5] However, precise constraints on the core structure and mass remain difficult to derive and model-dependent. This is due to an intrinsic limitation of gravitational sounding: gravitational moments are only weakly sensitive to the structure of the inner regions.[6]

As demonstrated by several authors,[7],[8] seismology is able to provide more precise internal structure, down to the core, and internal differential rotation. However, recording the acoustic oscillations remains challenging.

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Although 9 demonstrated that the imaging Doppler technique is suitable for this task, it has been limited so far to low degree modes detection. Moreover, a precise identification of the detected mode frequencies could not be obtained. The only way to overcome these difficulties is to get almost continuous observations, for several weeks or so. A space experiment would be ideal for that goal. That is why we proposed the Echoes instrument in the frame of the JUICE mission.[10] In absence of such a project for the coming decade, the possibility remains of a ground-based network, able to provide more that 50% time-continuity. This was the origin of the JOVIAL network.[11] The choice of the sites was the result of the necessity to find telescopes of the class 1-2m available for long observing run, regularly spaced around the world.

Figure 1. The JOVIAL network telescopes location around the Earth

Table 1. Position of the observatories involved in the JOVIAL network

Country	Observatory	Latitude	Longitude
Japan	Okayama Observatory	+34° 34' 37.47" N	133°35'38.24" E
France	Calern Observatory	43.7423°N	6.9393°E
USA	Sunspot Observatory	32.7882°N	105.8195°W

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 oscillations. This section describes the principle and design of the JOVIAL instrument, which was build in three copies for each site of the network.

2.1 Measurement principle

The JOVIAL instrument is an interferometric velocimeter. It produces images of the velocity field of Jupiter by measuring the Doppler shift of solar lines reflected at the surface. It is based on a Mach Zehnder design, 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).

2.1.1 Equations

The interferometric pattern can be described by the following equation:

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

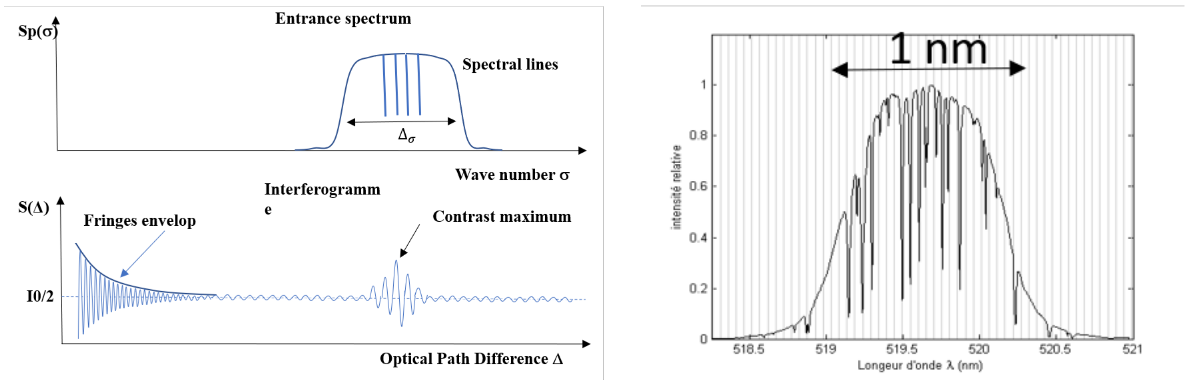


Figure 2. Left: Interferometric pattern as a function of the Optical Path Difference in the interferometer due to the presence of spectral lines in the entrance filter. The phase of the fringes at the output varies with the Doppler velocity shift of the spectral lines. Right: the actual entrance filter with the solar lines. The central wavelength is 519.5 nm and the bandwidth is 1 nm. The almost regularly spaced spectral lines produced a maximum of fringe contrast at an OPD of 5.035 mm.

where Δ is the Optical Path Difference and S_p is the entrance spectrum. Due to the presence of several spectral lines, the output I has several maxima at large value of the OPD. Around a maximum, the fringes are well described by:

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

where I_0 is the mean intensity, γ 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 12 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 (Fig. 2). This corresponds to a set of solar spectral lines regularly spaced in wavelength. The corresponding theoretical contrast γ is about 5%.

The Mach-Zehnder design provides 4 images of the target on which the interferometric fringes are superimposed. It can be seen from the previous equations that the phase of the fringes provides a direct measurement of the Doppler shift velocity of the surface of the target. We use this principle to design a velocity imager. The phase of the fringes can be recovered from the images through the so-called ABCD method, i.e. by measuring 4 points along the fringe separated by $\pi/2$ in phase.

2.2 Design and implementation

The JOVIAL instrument derives from the Doppler Sismo Imager (DSI) prototype that was developed in view of a possible space instrument.[10] The DSI instrument aims to provide velocity fields at the surface of the planet by measuring Doppler shift along the image of the planet. 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 conduct to a new design of the instrument.[13] The main goals of the new design was the possibility to use larger telescopes and an improvement of the quality of the vacuum tank to be insensitive to external temperature fluctuations.

2.2.1 Optical design

Previous tests were realised at the 1m C2PU telescope at Calern observatory. The possibility to use larger telescopes was contemplated, in particular for observations of Saturn. Between the accessible telescopes, the 188cm telescope at Okayama was a first option because its large diameter, its easy access for long periods and its location around the Earth, well completing locations in France and the USA. Access to telescope as large as the 3.5m telescope of the Astrophysical Research Consortium at Apache Point Observatory was also considered.

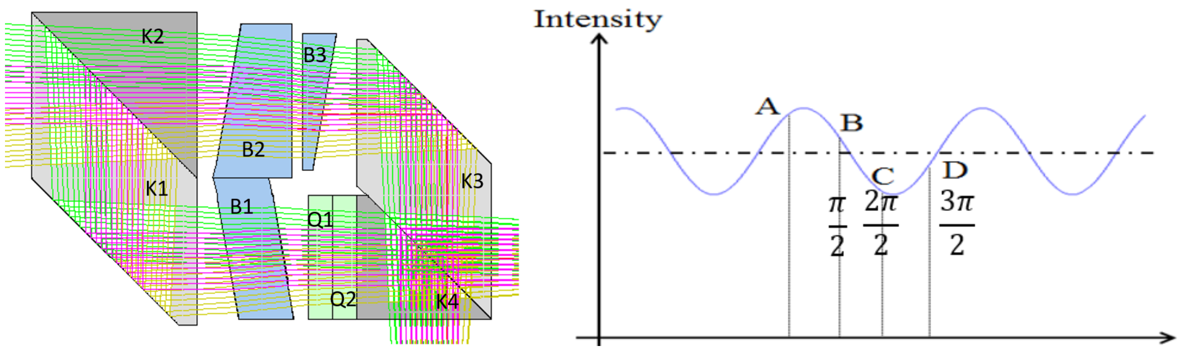


Figure 3. Left: View of the Mach-Zehnder interferometer. The entrance beam enters through the rhomboid K1 and is split in two beams. On one arm, the optical plate is separated in two parts, B2 and B3, where B3 can be shifted to modulate the OPD. On the other arm, a quarter wave plate, composed of the quartz plates Q1 and Q2, introduces a phase shift of $\pi/2$ between vertical and horizontal polarizations. The two outputs are separated in the two polarizations, providing four beams on the detector. Right: The instrument allows the measurement of the interferometric fringes in 4 points separated by $\pi/2$ in phase. We can build the two quantities (A-C)/(A+C) and (B-D)/(B+D) which are respectively the sine and cosine of the phase angle.

This implied a modification of the output optical path in order to minimize the beam size at the output. A complete new design was then conceived. It allows to locate the polarizers and the entrance filter inside the vacuum tank for stability. A good optical scheme permitted to use the entry and output lenses as windows for the vacuum tank, minimizing also the number of surfaces. The figure below shows the optical beam inside the vacuum tank and the MZ, as well as a detail of the four outputs, aiming to the four beams on the detector. The present scheme is compatible with telescopes up to 2.4m, but could be extended to a 3.5m telescope with a larger detector.

The optical analysis shows that the quality of the image remains excellent in a field of view of 1.24 degree, inside the Mach-Zehnder, corresponding to a FoV on the sky of 59 arcsec. The pupil size inside the MZ is 15.7mm.

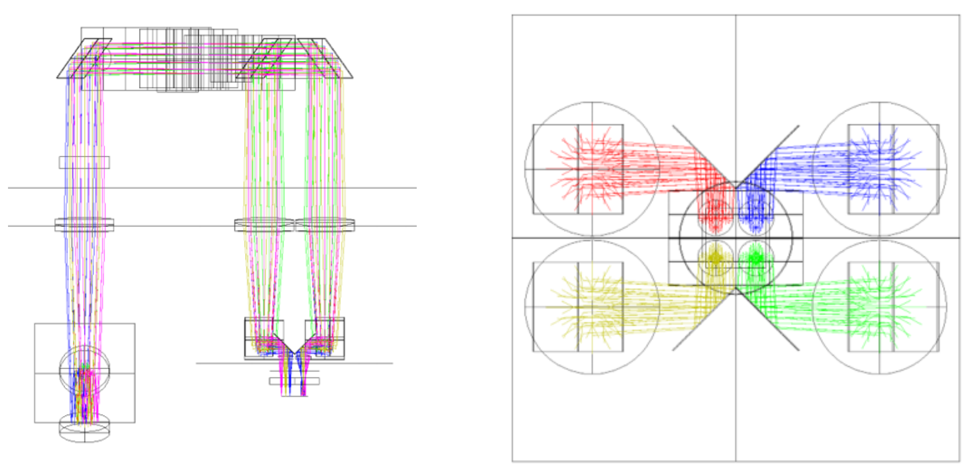


Figure 4. Optical scheme of the Mach-Zehnder interferometer and its entrance and output beams. The upper part represents the Mach-Zehnder located inside the vacuum tank. Lenses at the entrance and outputs are used as windows of the vacuum tank.

2.2.2 Thermal study

The DSI prototype was inserted in a vacuum tank provided by IAS in the frame of Research and Development program founded by CNES, in view of a proposal for a space instrument. It was supposed to be a laboratory test

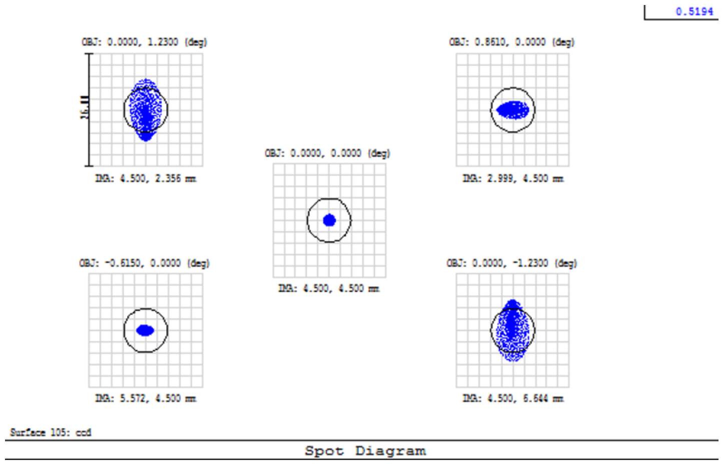


Figure 5. The Zemax analysis shows the optical quality of the four outputs on the whole Field of View of 60 arcsec

facility and was not designed for use behind a telescope, were the thermal environment is not always constant. Moreover, the new optical scheme modified the implementation of the instrument inside the tank. In particular, the separation of the two outputs in perpendicular polarisation had to be included inside the vacuum tank. The entrance filter was also located inside the tank to improve its internal stability. However, the possibility to remove the filter for tests was required. In the new design, the filter is then placed on a rotation mount which could be switched from the outside.

The new design of the vacuum tank included a full thermo-mechanical study. The stability and uniformity of the temperature inside the tank has to remain within specifications above a range of external temperature variations. The tank includes an external tank allowing a vacuum down to 10^{-5} Torr, to minimize the heat flux between the inside and the outside and a copper oven where the optical plate is located, regulated by an fluid exchange with a Lauda themal regulator. The design permits to minimize the heat flux through the windows and the coupling between the internal oven and the external tank with MLI. The feet that support the oven and the optical plate decouple the external temperature from the oven. One difficulty came from the internal piezo mechanism used for calibration. It has appeared that the piezo plate in DSI was producing heat, affecting the uniformity of the MZ temperature. This point was specifically addressed in the thermal study. The new piezo plate is supposed to produce less heat. However, an additional mitigation was added by inserting a copper thermal link between the piezo plate and the oven. The study proved that the specifications of thermal uniformity of 0.1 °C and stability of 0.01 °C could be respected with external temperature between 15 and 35 °C.

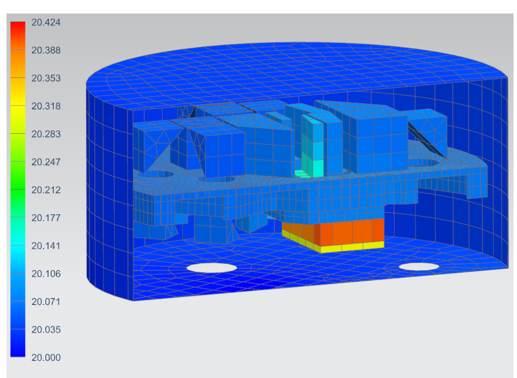


Figure 6. The thermal study shows the stability and homogeneity of the Mach-Zehnder inside the oven, for several outside temperatures, here 22°C. The B3 plate, used for calibration is slightly heated by the piezo device, but most of the heat is evacuated by a thermal link between the plate and the oven.

2.2.3 Mechanical realisation and installation

After the delivery of the vacuum tank, the Mach-Zehnder interferometer was integrated inside the tank and tested at the laboratory in Nice. The gluing and the adjustment of the Mach-Zehnder was quite challenging.

The optical concept of the Mach-Zehnder interferometer is based on right-angle and rhomboid prisms glued together to form the beam-splitters. For thermal compensation, the central part of the setup (in blue in figure 3) is made in N-BK7, while the right-angle and rhomboid prisms are in K5G20.

Optical bonding is obtained with UV-curing NOA61 glue. For optical quality, the UV lightning of the glue film should be as uniform as possible, which was very difficult to achieve, in particular with K5G20 glass, poorly transparent to UV light. Moreover, the quality of the fringes (contrast uniformity and level) is critically linked to differential aberration and tilt between the two beams of the interferometer. In this concept, tilt adjustment is obtained by adjusting the optics before UV-lightning. We encountered many difficulties in this operation, as the glue always retracts during curing. For a new instrument, a more simple optical design based on commercial cube beam-splitters and right angle prisms, with no glued optical dioptric surfaces, is foreseen.

However, acceptable optical quality was finally obtained, with a final wavefront of 40 nm rms. This was at the origin of a non-uniform contrast, with a maximum value of about 3 % and an average value of 2.5% on Jupiter, to be compared with a mean contrast of 3.5% with the DSI instrument. One of the reason of this loss of contrast is the larger pupil size (16mm) inside the Mach-Zehnder and the remaining astigmatism of the differential wavefront inside the Mach-Zehnder.

After the realisation and integration of the Mach-Zehnder,the whole instrument was assembled and tested. An exploded view of the opto-mechanical model is presented in Fig. 7. Tests were achieved at the laboratory in January 2019, before the shipping of the instrument to Japan.

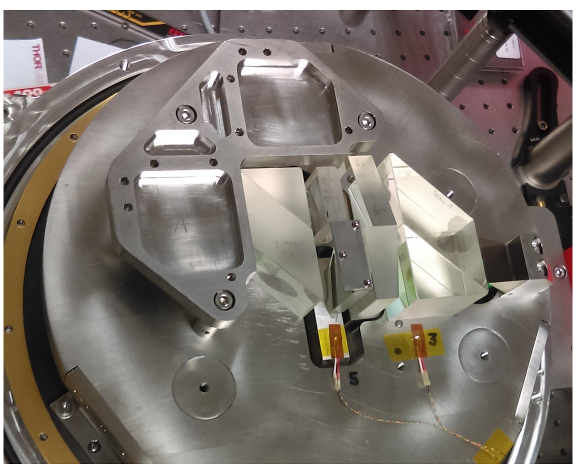
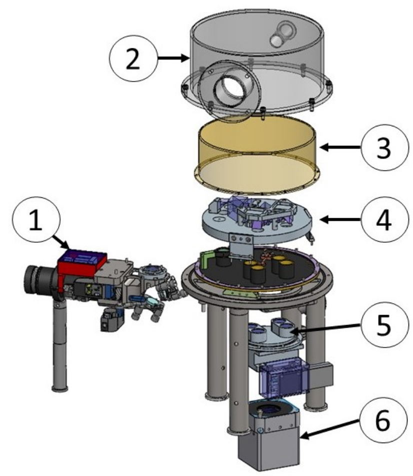
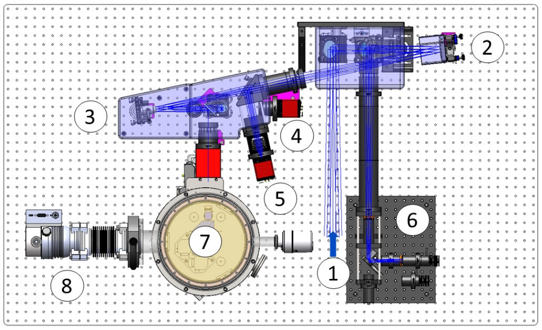



Figure 7. Left: View of the Mach-Zehnder glued on the mechanical structure, to be inserted in the oven. On the right: exploded view of the JOVIAL opto-mechanical setup: 1-input optics and calibration grid system, 2-vacuum tank, 3-copper oven, 4-Mach-Zehnder, 5-output optics, 6-detector

The instrument was installed in the Coudé room of the 188cm telescope at Okayama observatory in March 2019. The whole instrument is placed on a breadboard with compensated feet. The Coudé room itself is regulated in temperature.

3. PRELIMINARY RESULTS AND PERFORMANCES

Observations of Jupiter where conducted between May 29th and June 16th. The weather is usually not very good in June in this area in Japan. However, the goal was to check the instrument and to try simultaneous observations



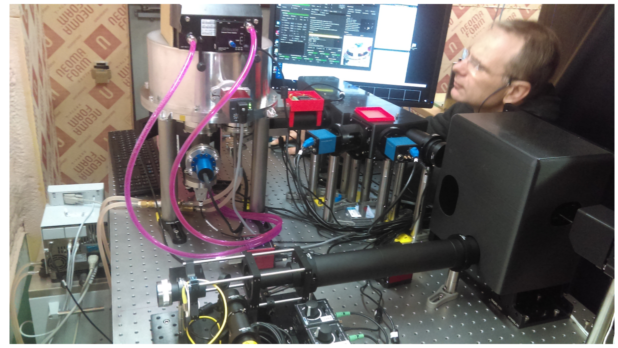


Figure 8. Installation of the JOVIAL instrument at the Coude room of the 188cm telescope at Okayama. A 900 x 1500 mm breadboard has been installed at the output of the Coude beam. On the left, the optical scheme of the optical interface between the telescope and the instrument: 1-beam from telescope, 2-slow pupil control mirror, 3-fast image stabilization mirror, 4-pupil camera, 5-image camera, 6-calibration source, 7-Mach-Zehnder, 8-turbo pump. The beam adaptation to the Mach-Zehnder includes a grid for geometrical calibration. On the right, a photo taken during the installation. Pipes for thermal regulation of the vacuum tank and the camera are visible. The thermal regulator was finally placed outside the room to keep the stable environment without excess heat.

with New Mexico. Nine nights provided observations, but only three had adequate weather conditions. The first day of observation, June 29th, was the best of the series and almost 6 hours were obtained. The full processing of the night provides observations of more than half the surface of Jupiter.

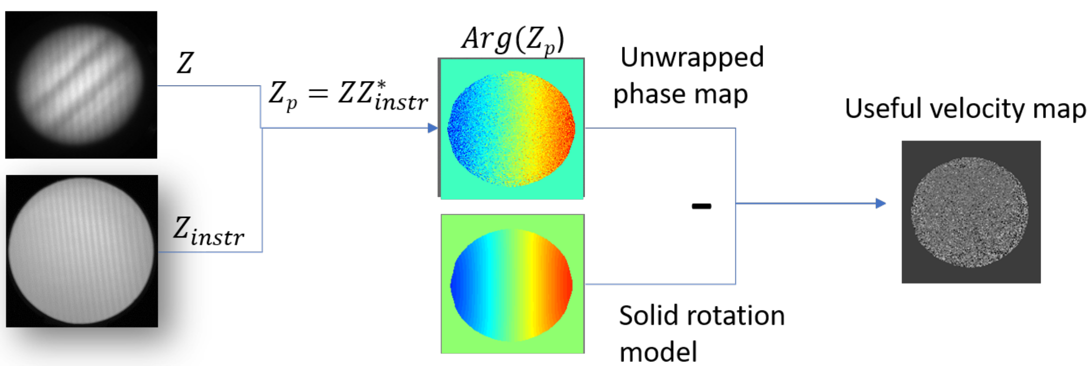


Figure 9. Schematic view of the data processing: Instrumental fringes obtained from calibration are subtracted from the fringed image. The argument of the complex pattern gives the phase, which is proportional to the velocity field, dominated by the fast planet rotation. A model of the rotation is applied to get the remaining velocity containing the dynamics and the oscillations.

The full data processing is described in 14. Interferograms are transformed into flux and Doppler velocity images. At its time, this Doppler image is used to calculate zonal and meridional components of the wind at the surface, using the projection factors. The fast rotation of the planet would allow to reconstruct the wind all around the planet in less than 10 hours of continuous observations. Here, we show the results of one single night, with less than 6 hours of observations. The processed zonal velocity data is displayed on a planisphere of the planet on Figure 10. It shows the fast jets in the equatorial zone, the retrograde velocity in the northern band, and the Great Red Spot in the South. The detailed structure around the GRS shows the potential of the Doppler imager to get data about the dynamics in the atmosphere in a complementary way with cloud tracking.

Actually, the zonal analysis that we applied here does not give exactly the zonal velocity. Because of the finite size of the PSF, Doppler shift measurement is an integral term of the velocity field and the photometric flux 15, 16. The proper inversion of this integral equation requires a complete model of the velocity field to be applied to the data. It would allow the extraction of the full dynamics. The shape of the PSF should be included in this model. Nevertheless, the direct view obtained by applying the projection factor gives a clear idea about the dynamical structure, showing the fast anticyclonic rotation around the GRS. It is a guide for further analysis of the same data. Obviously, ground based data perturbed by atmospheric turbulence cannot have the same quality as space data, for which we can know almost exactly the shape of the PSF. Having such an instrument on board of a spacecraft in orbit around the planet would be extremely useful.

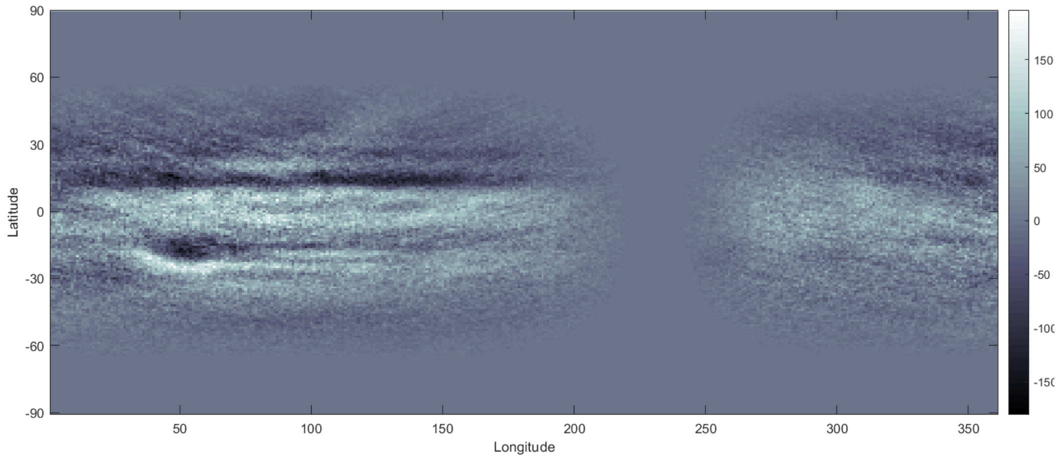


Figure 10. Planisphere of the zonal winds obtained on May 29th, 2019. The vertical scale is in m/s, counted positively for prograde winds. The Great Red Spot is clearly visible at latitude -20° and longitude 50°.

The noise level of these observations is still to be compared with previous observations. The maximum number of photons collected on Jupiter was only twice what we obtained with previous observations in Calern in 2016, although the ratio of diameter should give a flux ratio of 3.6. This is due to a lower altitude of the observatory and a lower culmination of Jupiter at maximum 32 degrees against 55 degrees at Calern in 2016, and very probably to the transmission of the Coudé train. We estimate from the measured flux a total transmission of the Coudé train between 60 and 65 %. So the gain in photon noise would only be a factor of $\sqrt{2}$ lower with respect with the 1m C2PU telescope in Calern. On the other hand, the contrast loss is of the same order, meaning that we should get almost the same noise level as with the previous observations done in Calern in 2016.

Despite theoretical performances almost identical to previous observations, the detailed Doppler signal seems to be more accurate in the center of the field, where the contrast was maximum, leading to the clear image of the GRS obtained in just a few hours. The noise level is approximately 4 m/s per pixel in the image. The noise increases however quite fast on the edges of the image, that is why zonal winds at latitude higher than 40 degrees cannot not recovered with confidence.

Instrumental changes occurred during the run, which affected the data quality after June 4th. Some spurious spots appeared within the beam, which may be due to humidity. It resulted in a strange pattern superimposed on the velocity map, which cannot be easily corrected. This behaviour could have been corrected by additional calibration, which was not done at that time as the problem was not identified immediately. An intervention is anyway required before the next observations to clean the optical surfaces.

All the data obtained has been processed but only the data before June 4th have been included in the analysis for the atmospheric dynamics. Nevertheless, the goal of the project is mainly to get a low noise level for computation of the oscillations spectrum and these spots does not affect much the noise level for the oscillations modes, at least for the low degree ones. For that goal, the large diameter of the Okayama telescope is a clear advantage. However, a good continuity with the full network is still the main way to improve the performances for seismology. The last campaign was too short, with too many bad weather episodes to get a real improvement of the final spectrum noise level. In the coming years, the situation will be much more favorable, starting in

2021. In 2023, we expect to have optimal conditions, with a higher flux and much longer nights. A possibility to improve the contrast by replacing the Mach-Zehnder by the last version (see below) is also envisioned.

4. CONCLUSION AND PERSPECTIVES

We have seen that the first tests of the JOVIAL instrument were achieved at Okayama observatory between May and June 2019. Despite adverse weather conditions, good data could be obtained for at least a few nights, enabling the release of the first Doppler-image of Jupiter's winds (Figure 10). This image is still preliminary, but it highlights the great promise of Doppler-imaging of solar system planetary atmospheres: the possibility to measure the three components of atmospheric winds (zonal, meridional and vertical). We anticipate that with further observations, much higher quality data can be obtained. For example, due to weather, observations so far were not simultaneous between Okayama and the Dunn Solar Telescope in New Mexico. Future observations including all three sites will be much more sensitive.

After the installation and first observing run in 2019, 2020 was supposed to be the first run with three instruments simultaneously observing Jupiter during the month of July. However, the pandemic crisis did not allow the realisation of this plan. The impossibility of travel and the 6 months delay on the realisation of the last instrument has obliged us to report the foreseen observations to August 2021. We plan to observe both Saturn and Jupiter, which both will be observable at that time. The observing conditions should be much more favorable than in 2019, with better weather in Japan in particular and higher altitude of the planets in the sky, ensuring a larger continuity of the observations. However, the length of the nights will still not be very long. Better observing conditions will be encountered in 2022 and moreover in 2023. We expect that we can observe both Jupiter and Saturn at that date with the JOVIAL network.

In 2020, despite the problems with the pandemic, we also installed and tested an adaptive optics system at the C2PU telescope in Calern observatory. This AO system is designed for planetary observations, as it could allocate the full field of view of 50 arcsec corresponding to the maximum apparent diameter of Jupiter within the Shack-Hartman Wave Front Sensor. Such a system would allow a partial correction of the atmospheric turbulence, up to an altitude of 3000 m, for a 50 arcsec FoV and for a 1m telescope. This ground layer usually contains more than 70% of the total turbulence. It would improve the quality of the observation and stabilize the Point Spread Function (PSF), allowing a better data processing result. We expect that this system will be operational in the coming months and will be ready for the next observing run in August 2021. All the data obtained so far has been processed and are available through the JOVIAL database, held at IAS in the IDOC database. It will be made available publicly through the Planetary Surface Portal (PSUP) interface.

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