

## Article

# Jupiter's Atmosphere Dynamics Based on High-Resolution Spectroscopy with VLT/ESPRESSO

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**Abstract:** We present a new study of Jupiter's atmosphere dynamics using for the first time the extremely high-resolution capabilities of VLT/ESPRESSO to retrieve wind velocities in Jupiter's troposphere, with a dedicated ground-based Doppler velocimetry method. This work is primarily a proof-of-concept for retrieving Jupiter's winds using VLT/ESPRESSO Doppler velocities. These results are complemented by a re-analysis of Cassini's data from its fly-by of Jupiter in December 2000, performing cloud tracking at visible wavelengths, for cross comparison with Doppler velocimetry results, along with previous cloud-tracking results. We explore the effectiveness of this refined method to measure winds in Jupiter, using high-resolution spectroscopy data obtained from ESPRESSO observations performed in July 2019, with a Doppler velocimetry method based on backscattered solar radiation in the visible range. Coupled with our ground-based results, we retrieved a latitudinal and longitudinal profile of Jupiter's winds along select bands of the atmosphere. Comparing the results between cloud-tracking methods, based on previous reference observations, and our new Doppler velocimetry approach, we found a good agreement between them, demonstrating the effectiveness of this technique. The winds obtained in this exploratory study have a two-fold relevance: they contribute to the temporal and spatial variability study of Jupiter's troposphere dynamics, and the results presented here also validate the use of this Doppler technique to study the dynamics of Jupiter's atmosphere and pave the way for further exploration of a broader region of Jupiter's disk for a more comprehensive retrieval of winds and to evaluate their spatial and temporal variability.

**Keywords:** Jupiter; atmosphere; spectroscopy; atmosphere dynamics; Doppler velocimetry



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## 1. Introduction

With a growing list of large, gaseous objects being detected throughout the galaxy over the past two decades, astronomers are now eager to characterise these faraway worlds, particularly their atmospheres. Due to their proximity, the gas and ice giants of the Solar System should serve as archetypes for these new worlds, with Jupiter already being used as a template to compare with the majority of exoplanets and Brown Dwarfs discovered.

Jupiter's alternating banded structure remains one of the most compelling aspects of its atmospheric structure and its connection to upper cloud dynamics. However, despite the use of numerous interplanetary and orbiting spacecraft combined with a long record of Earth-based observations, some fundamental questions regarding dynamical processes in Jupiter's atmosphere remain [1]. The vertical structure of the colourful clouds and their circulation mechanisms are still elusive regarding the drivers of zonal flow and vertical transport within and between the bands that can be observed at visible wavelengths [1–4]. In addition, to study the atmosphere dynamics of solar system planets, particularly its behaviour and evolution with time, continuous observations are helpful [5].

There is an extensive record of observations of Jupiter's upper troposphere at visible wavelengths from ground-based telescopes to several fly-by and orbiter space missions.

For most observations of this atmospheric region, which is presumed to be between a 0.7 and 1.5 bar pressure range [6], the cloud-tracking technique was employed to evaluate the dynamics of both the general banded structure of Jupiter and also the several storm and turbulent systems that populate the observable disk. Major contributions to the analysis of the zonal winds on Jupiter at visible wavelengths include observations from older missions [7,8], a plethora of data from Cassini during its fly-by in December 2000 [9–13], Hubble Space Telescope (HST) observations [14–17] and, more recently, from the ongoing Juno mission through high-resolution images from JunoCam [18]. Additionally, with more widely available equipment suitable for scientific observations, amateur astronomers are increasingly collaborating with professionals in this regard, offering continuous coverage of several targets, including Jupiter [15,19,20].

Even though this volume of data, complemented by other kinds of observations, such as infrared and radio, allows in-depth exploration of the dynamics of Jupiter's atmosphere, winds at tropospheric levels have mostly been obtained with cloud-tracking techniques, which follow large patterns moving in the observable atmosphere of Jupiter. Recent efforts in studying the dynamics of the tropospheric region of Jupiter with other techniques such as high-resolution spectroscopy are gaining momentum, with the improvement in facilities enabling increased spectral resolution. This has allowed the first successful application of a Doppler velocimetry method on Jupiter, reported recently in Goncalves [21].

With cloud-tracking methods, movements of large cloud patterns are followed, leading to wind velocity results of relatively larger scale structures depending on image resolution. Doppler velocimetry techniques allow the retrieval of the instantaneous velocity of cloud particles. Each method can lead to distinct wind results should cloud structures tracked by the first method be influenced by atmospheric waves. Additionally, since the Doppler velocimetry method does not rely on imaging data, it is possible to extract wind speeds on a largely featureless atmosphere such as Venus or Uranus at visible wavelengths [21,22].

Situated atop *Cerro Paranal* in the Atacama Desert, Chile, stands the Very Large Telescope array (VLT), one of the leading facilities for European visible light astronomy at the Paranal Observatory. One of the most modern instruments placed at the VLT is the *Échelle SPectrograph for Rocky Exoplanets and Stable Spectroscopy Observations* (ESPRESSO), a fibre-fed, cross-dispersed, high-resolution échelle spectrograph located in the Incoherent Combined-Coudé Laboratory (ICCL) where it can be fed the light of either one or all four Unit Telescopes (UT) [23]. ESPRESSO is able to obtain two simultaneous spectra in a wavelength range between 378.2 and 788.7 nm with a resolving power that ranges from 70,000 in the Medium Resolution mode (MR) to more than 190,000 in the Ultra-High-Resolution mode (UHR) [24]. ESPRESSO was originally designed for exoplanet hunting and atmospheric characterisation; however, just as was demonstrated in [25] for HARPS-N, using these very high-resolution spectrographs on Solar System atmospheric characterisation can open new horizons on what is possible to achieve with ground-based instruments to study large objects in our cosmic vicinity.

In this work, we optimised a Doppler velocimetry method previously applied to retrieve winds on Venus' cloud top region in the visible part of the spectrum [26–29]. This work presents an exploration of other targets within the solar system with an adaptation of this technique to Jupiter. It is also an opportunity to investigate the effectiveness of ESPRESSO in the study of Solar System atmospheres since it was used for this purpose for the first time.

The magnitude of the jets in Jupiter's atmosphere and their evolution in time have been studied extensively over decades, in part using cloud-tracking techniques [2]. These observations revealed that eastward and westward winds have very similar magnitudes, with the exception of the equatorial zone, which favours an eastward wind velocity that can reach 150 m/s [30]. Additionally, the jets do not appear to be symmetric in relation to the equator: there is a stronger jet at 24° N that has no southern counterpart; the Great Red Spot (GRS) in the southern hemisphere; and even within the equatorial jet there is an apparent asymmetry from the presence of a trapped Rossby wave between the Equatorial Zone and the North Equatorial Belt [31].

In this work, we present results on the zonal wind flow at the Equatorial Zone (EZ), and the North and South Equatorial Belts (NEB, SEB), retrieved with Doppler velocimetry with VLT/ESPRESSO ground-based observations using all the lines in the Fraunhofer spectrum within the full wavelength range of VLT/ESPRESSO from backscattered solar radiation from Jupiter’s atmosphere. As this was an exploratory effort, the latitude coverage of our results is limited; however, it shows moderate consistency with previous results with various instruments. This work can pave the way for the exploration of other Solar System targets with ground-based observations to fill the gap left by the limited availability of interplanetary space missions, ensuring continuous monitoring of the evolution of the atmospheric circulation on those planets at a high resolution. Moreover, this technique holds promise for analysing short-timescale wind variability.

## 2. Observations with VLT/ESPRESSO

We observed Jupiter with ESPRESSO between the 21 and 22 of July 2019. The goal of these observations was to retrieve zonal wind measurements in the banded structure of the planet, taking advantage of the unprecedented spectral resolution of ESPRESSO, which allows a precision that can go lower than 1 m/s with our Doppler velocimetry method.

With ESPRESSO, Jupiter was observed for approximately 5 h between the late hours (23:00 UT) of 21 July and the early morning (04:20 UT) of 22 July 2019. However, the first hour of observations was mostly used for calibration efforts and pointing accuracy verification; hence, no science data were taken during that period. At the time of observation, the planet presented an apparent magnitude of  $-2.61$ , an angular diameter of 45.92 arc seconds and an illuminated fraction close to 99.986%, a very high fraction as is expected from planets beyond Earth’s orbit from the Sun. Together they correspond to a surface brightness as seen from Earth of the order of 5.44 mag/arcsec<sup>2</sup>. All observational values were taken from [32]. Observations were carried out as a time series of 60 s exposures at predetermined positions on Jupiter’s visible disk, aligning each observation sequence with latitudinal bands of the atmosphere. The UHR mode was used for the best possible resolution ( $>190,000$ ); thus, the most precise measurements of the Doppler shifts (at the wavelength range 378.2–788.7 nm). For these observations, the FOV of the instrument was approximately 0.5 arc seconds, represented as small circles on Figure 1, which also shows the placement of the fibre’s FOV on the visible disk of Jupiter.

We summarise the observing conditions and geometry of the target during observations in Table 1.

**Table 1.** Summary of target characteristics during ESPRESSO observations of Jupiter.

| (1)<br>Date | (2)<br>Time (UT) | (3)<br>$\Phi$ (°) | (4)<br>Ang.Diam. (") | (5)<br>Sub-Obs.Lat (°) | (6)<br>Air Mass |
|-------------|------------------|-------------------|----------------------|------------------------|-----------------|
| 21/22 July  | 23:03–04:20      | 7.7               | 45.92                | −3.05                  | 1.003–1.254     |

The date (1) and time (2) interval refer to the value registered by the instrument during observations; (3) is the phase angle; (4) is the size of the disk of Jupiter in the sky in arc seconds; (5) is the sub-observer latitude on Jupiter’s frame; and (6) represents the air mass at the target’s location in the sky during observations.

The observing routine employed was similar to previous efforts to retrieve Doppler shifts on Venus with both the HARPS-N [25] and the CFHT/ESPaDOnS [27] in the sense that scanning was made in sequences based on the same planetary latitude, which was particularly important due to the nature of the contrasting wind flow between each band at cloud level. To ensure stability during the observing run, our method relies on repeated observations of the reference point at the beginning and end of each sequence. However, during observations, it was verified that the instrument’s stability was sufficient so that this condition could be relaxed for the remainder of our observations, returning to the reference position after 2–3 sequences instead. At the end of acquisition, this decision proved efficient since it allowed better spatial sampling of Jupiter’s disk without sacrificing measurement accuracy due to instrumental instability. However, because ESPRESSO proved to be

remarkably stable and observing time was limited, the team chose to maximize the number of points on Jupiter's disk that could be observed, to capture the wind flow over several latitudinal bands. We performed two 60 s exposures for each position to ensure consistency between retrievals in the same position.

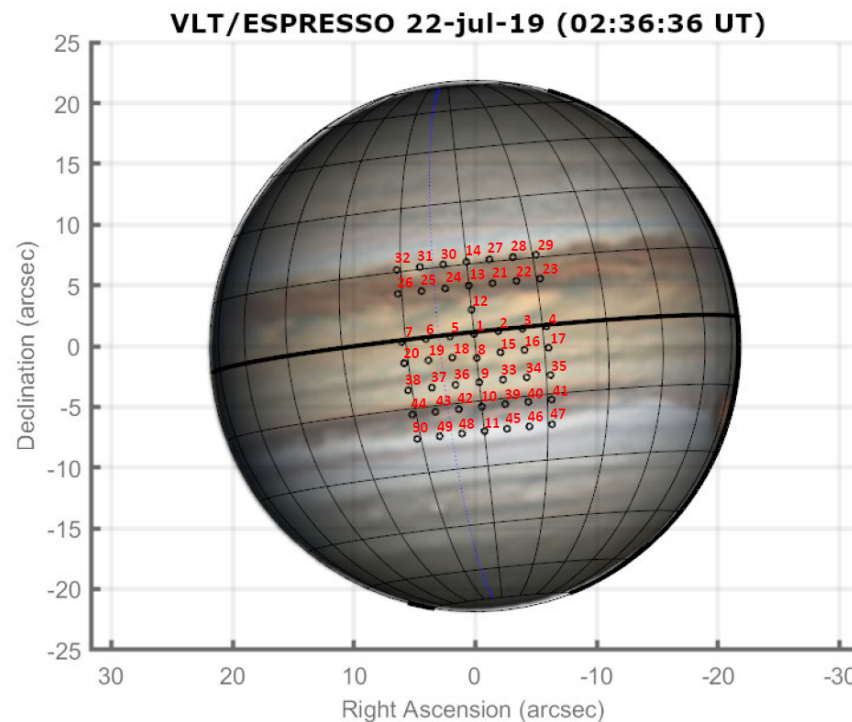


**Figure 1.** Schematic of the observing routine on Jupiter by VLT/ESPRESSO on the 22 July 2019. The small circles represent the FOV of the fibre proportional to the size of Jupiter's disk in the context of these observations (0.5 arc seconds in diameter for the size of the FOV), and their respective labels. We also included a grid to tentatively map the relative position of each observing position in latitude and longitude. Grid lines have intervals of  $15^\circ$  on both coordinates. The solid black line on the right side of the spherical grid represents the morning terminator, while the blue dotted line marks the location of the 12 h local time meridian. The picture of the planet's disk was taken from the Planetary Virtual Observatory and Laboratory. Picture credits go to Gary Walker.

### 3. Doppler Velocimetry with VLT/ESPRESSO

Here we describe the adaptation of our Doppler velocimetry method to the case of Jupiter. This technique has already been proven to be highly effective and precise in the study of Venus' atmosphere dynamics and in the retrieval of wind measurements based on high-resolution spectra observations [21,26–29]. Contrary to the cloud-tracking technique where we gather averaged winds over a set time interval (determined by the temporal distance between the two images in the pair) for large cloud structures, since the minimum size of features is directly reliant on image resolution, the Doppler velocimetry method provides instantaneous wind velocity measurements using Fraunhofer lines (characteristic absorption lines from gas in the Sun's photosphere when interacting with continuum radiation emitted from warmer and deeper layers of our host star) in the visible part of the spectrum scattered by cloud particles of the target atmosphere (in our case Jupiter). The Doppler shifts manifested in the Fraunhofer lines of the backscattered sunlight from particles in the atmosphere, which move with some relative velocity with respect to our frame of reference, are used to compute instantaneous velocity values of particles in the atmosphere [28].

#### 3.1. Projected Radial Velocities

Although the Doppler velocimetry technique is thoroughly described in Machado [26,27] and Goncalves [21], for the case of Venus atmospheric studies using the high-resolution

spectrographs ESPaDOnS/CFHT and HARPS-N/TNG, we describe it again here for clarity reasons and since the adaptation of the Doppler velocimetry method for the case of ESPRESSO/VLT observations of Jupiter is performed here for the first time. One of the great challenges pertaining to ground-based observations of planetary winds lies in maintaining a stable velocity reference when acquiring data. Several different techniques that use high-resolution spectroscopy to retrieve planetary winds in the visible part of the spectrum have addressed this issue [21,26–29,33–36]. The reason for this challenge is that radiation dispersion laws and inherent instrumental uncertainties have constrained absolute reference rest frames with accuracies no better than about 100 m/s to measure winds directly, while global winds on most planetary targets, while substantially different, can have wind amplitude variations or latitudinal gradients of the order of 5–10 m/s projected on the line-of-sight. However, with the recent use of instruments such as HARPS and ESPRESSO, primarily used for exoplanet search and characterisation, we can retrieve wind velocities with extreme precision, lower than 5–10 m/s. The Doppler velocimetry method used in this work is based on an optimal weighting of the Doppler shifts of all the lines present in the spectrum, relative to some reference spectrum.

This is accomplished by performing a weighted average of all the lines in the Fraunhofer spectrum using the inverse of the variance as a weighting factor:

$$\delta v = \frac{\sum \delta v_i \omega_i}{\sum \omega_i} \text{ where } \omega_i = \frac{1}{\sigma^2[\delta v_i]} \quad (1)$$

where the weighting factor  $\omega_i$  is the inverse of each individual line contribution to the variance. To consider this, we must assume the representative noise when gathering.

The Doppler shift present in the lines of the solar backscattered spectrum results from two instantaneous motions. One motion is between the Sun and Jupiter's upper cloud particles whose Doppler shift is minimal near the planet's sub-solar point and maximum at the sub-terrestrial point (observer). Another is between the observer and the planet's atmosphere, resulting from the topocentric velocity of cloud particles in the target's atmosphere in the observer's reference frame whose Doppler shift reaches its lowest value close to the sub-terrestrial point and its highest at the sub-solar point. These combined motions add up and contribute to a spatial variation in the Doppler shift as a function of the latitude and longitude on the target.

Since solar radiation is scattered from both Jupiter and Earth's atmospheres, and taking into account that some Fraunhofer lines are absorbed by our atmosphere, the contribution from telluric lines needs to be accounted for. To this end, the instrument registers both spectra and a least-squares deconvolution is applied to the pattern of Fraunhofer lines, using a mask that matches the Sun's stellar type (G2 type star), providing the radial velocity (along the line-of-sight) in the solar system barycentric frame (B). From the correlation function between the Fraunhofer lines scattered from Jupiter and Earth, a double Gaussian fit is applied to extract the velocity  $h$  of the radiation scattered off of the target only. However, to calculate this velocity, other components are introduced to account for additional contributions to the Doppler shifts of the lines, and it is necessary to express these measurements in Jupiter's centre (of mass) rest frame:

$$w_i = h - (berv + v_{topo} + v_{rot}) \quad (2)$$

where  $w_i$  is the radial component of the instantaneous velocity of the planet's clouds in the observer's direction expressed in the centre rest frame of the target (P),  $h$  is the absolute velocity of solar lines scattered off the planet's clouds expressed in the barycentric frame (B),  $berv$  is the correction from Earth's rotation and orbital motion, i.e., the observer's movement in the barycentric frame (B),  $v_{topo}$  is the instantaneous velocity of the planet's centre of mass in the topocentric frame (T) and  $v_{rot}$  is the contribution of the Doppler shift from the differential rotation of the planet. The values for the velocities  $berv$  and  $v_{topo}$  are taken from the ephemerides calculated by an online platform hosted by JPL/NASA (<https://ssd.jpl.nasa.gov/horizons.cgi> accessed on 15 November 2023). Contrary to previous

works [21,26,27,29,37,38], the planet's rapid rotation contributes with a non-negligible influence in the measured Doppler shifts. For this purpose, we used the standard rotation velocities from the System III [39] for the gas giant, which gives it a spin velocity at the equator of approximately 12.6 km/s.

Due to the extended angular size of the Sun as seen from Jupiter ( $\sim 0.1^\circ$ ) and its fast rotation ( $\sim 2$  km/s), a differential elevation of the finite solar disk near the terminator leads to an imbalance between the contribution of the approaching (blue shifted radiation) and receding (red shifted radiation) solar limbs. In this geometric configuration, the excess of one or the other has an effect on the apparent line Doppler shifts measured on the planet's atmosphere. This phenomenon is called the "Young effect", first noticed by [40] and its implications on Doppler velocimetry methods in [22]. Although it can be relevant for other targets within the Solar System, the Young effect, when calculated for Jupiter, has an influence of less than 0.1 m/s, which is minor when compared with the expected wind velocities in Jupiter (100–150 m/s).

### 3.1.1. De-Projection Coefficients

The velocities retrieved through the Doppler shift from Equation (2) are radial velocities; thus, they are projected along the line-of-sight. To obtain the amplitude of the wind velocities on the planet at each point observed in the planetocentric frame of reference, we need to compute the local de-projection factor (F).

$$F = 2 \cdot \cos(\Phi/2) \cdot \sin(\lambda - \Phi/2) \cdot \cos\phi_\beta \quad (3)$$

where  $\Phi$  is the phase angle at which the observation was performed,  $\lambda$  is the longitude of the point being measured on the disk and  $\phi_\beta$  is the latitude of the sub-terrestrial point. This factor is modulated by both the geometry of observations and the planetary longitude as seen from the ground. In the case of a zonal circulation, as is evaluated here, the line-of-sight Doppler shift is proportional to the projection of wind velocity on the bisector phase angle [29]. For each location probed on the disk of Jupiter as illustrated in Figure 1, these coefficients were calculated and then used to convert the extracted Doppler shifts to instantaneous velocities of particles in the atmosphere.

### 3.1.2. Instrumental Spectral Drift

The spectral acquisition of Jupiter's bands by VLT/ESPRESSO is sequential (see Table 2); thus, monitoring possible changes in spectral calibration with time is required to ensure measurement robustness. When the instantaneous velocity of the planet's centre of mass ( $v_{topo}$ ) is subtracted from the calculated velocity of atmospheric particles with the Doppler shift on the spectra retrieved, spectral wavelength calibration is performed at both the beginning and end of the observing session. In this case, this calibration was performed with a Th-Ar lamp exposure. Since the absorption lines from Earth's atmosphere are well known, their superposition to the target planet's spectra can be used as additional on-sky calibration.

As mentioned earlier, global wind circulation is found on most planets such as Jupiter, subject to wind amplitude variations or latitudinal gradients that can range between 5 and 40 m/s projected on the line-of-sight. Even though ESPRESSO is already capable of a good-enough spectral resolution, which can take into account such deviations with direct measurements, we took from previous experience [21,26,27,37,38] that better results can be achieved by measuring relative Doppler shifts between two sets of absorption lines. We arbitrarily chose the first spectrum of each series of sequential acquisitions  $w_{i,c,ref}$  as a velocity reference so that:

$$v_i = w_{i,c} - w_{i,c,ref} \quad (4)$$

where  $v_i$  represents the line-of-sight relative velocity, which results from the subtraction of the absolute velocity retrieved at some target point in the planet's disk ( $w_{i,c}$ ) and the velocity

in the reference point (Table 3). With each return to the point of reference, a slow drift of the velocity retrieved from this point becomes apparent, which presumably occurs due to imperfectly corrected instrumental effects and measurement of absorption lines from the Sun with respect to those from the Earth [36]. Since to calculate relative Doppler shifts we use a reference point during observations, this point is returned to several times to correct the velocities retrieved from the instrumental spectral drift and/or spectral calibration variability with time. The reference point chosen is located in the meeting point between the equator and the HPA meridian so that, theoretically, both the meridional and zonal components (respectively) of the winds gathered from the Doppler shifts should be null. Such properties make this point the ideal reference for the spectral drift by making several observations during sequence acquisition.

**Table 2.** Scanning sequences for Jupiter VLT/ESPRESSO observing run on 21/22 July 2019.

| (1)<br>Seq. Number | (2)<br>Location | (3)<br>Time Interval (UT) | (4)<br>Position Order |
|--------------------|-----------------|---------------------------|-----------------------|
| (1)                | Equator         | 00:18–01:02               | 1-5-6-7-1-2-3-4       |
| (2)                | S Lat 10°       | 01:06–02:28               | 9-36-33-34-1-37-38    |
| (3)                | N Lat 10°       | 02:33–03:01               | 1-13-24-25-21-22      |
| (4)                | N Lat 15°       | 03:05–03:17               | 14-31-28              |
| (5)                | S Lat 15°       | 03:20–03:43               | 1-42-43-39-10         |
| (6)                | S Lat 15–20°    | 03:47–04:20               | 48-49-45-46-11-40     |

(1) Sequence number; (2) location on disk; (3) time interval of the beginning and end of sequence (in UT); (4) points acquisition order. All positions were observed twice with a 60 s exposure each.

**Table 3.** Pointing geometry for VLT/ESPRESSO observations of Jupiter on July 2019.

| (1)<br>Position | (2)<br>$\lambda - \lambda_{SO} (^{\circ})$ | (3)<br>$\phi (^{\circ})$ | (1)<br>Position | (2)<br>$\lambda - \lambda_{SO} (^{\circ})$ | (3)<br>$\phi (^{\circ})$ |
|-----------------|--------------------------------------------|--------------------------|-----------------|--------------------------------------------|--------------------------|
| 1               | 0                                          | 0                        | 26              | −15.92                                     | 10.53                    |
| 2               | 5.24                                       | 0                        | 27              | 5.24                                       | 15.92                    |
| 3               | 10.53                                      | 0                        | 28              | 10.53                                      | 15.92                    |
| 4               | 15.92                                      | 0                        | 29              | 15.92                                      | 15.92                    |
| 5               | −5.24                                      | 0                        | 30              | −5.24                                      | 15.92                    |
| 6               | −10.53                                     | 0                        | 31              | −10.53                                     | 15.92                    |
| 7               | −15.92                                     | 0                        | 32              | −15.92                                     | 15.92                    |
| 8               | 0                                          | −5.24                    | 33              | 5.24                                       | −10.53                   |
| 9               | 0                                          | −10.53                   | 34              | 10.53                                      | −10.53                   |
| 10              | 0                                          | −15.92                   | 35              | 15.92                                      | −10.53                   |
| 11              | 0                                          | −21.45                   | 36              | −5.24                                      | −10.53                   |
| 12              | 0                                          | 5.24                     | 37              | −10.53                                     | −10.53                   |
| 13              | 0                                          | 10.53                    | 38              | −15.92                                     | −10.53                   |
| 14              | 0                                          | 15.92                    | 39              | 5.24                                       | −15.92                   |
| 15              | 5.24                                       | −4.59                    | 40              | 10.53                                      | −15.92                   |
| 16              | 10.53                                      | −4.59                    | 41              | 15.92                                      | −15.92                   |
| 17              | 15.92                                      | −4.59                    | 42              | −5.24                                      | −15.92                   |
| 18              | −5.24                                      | −4.59                    | 43              | −10.53                                     | −15.92                   |
| 19              | −10.53                                     | −4.59                    | 44              | −15.92                                     | −15.92                   |
| 20              | −15.92                                     | −4.59                    | 45              | 5.24                                       | −21.45                   |
| 21              | 5.24                                       | 10.53                    | 46              | 10.53                                      | −21.45                   |
| 22              | 10.53                                      | 10.53                    | 47              | 15.92                                      | −21.45                   |
| 23              | 15.92                                      | 10.53                    | 48              | −5.24                                      | −21.45                   |
| 24              | −5.24                                      | 10.53                    | 49              | −10.53                                     | −21.45                   |
| 25              | −10.53                                     | 10.53                    | 50              | −15.92                                     | −21.45                   |

(1) Point nomenclature (also present in Figure 1); (2) planetocentric longitude of point relative to sub-observer meridian (sub-terrestrial in this case); (3) latitude of the point's centre.

Since we assume that any variations in the Doppler shift measured on this reference point come from the spectral drift provoked by the instrument, we fit all the reference point

velocities to a series of linear segments  $v_{trend}$ , taking the initial velocity from the reference point to have a zero offset. With this trend line, it is possible to compute the offset caused by the spectral drift at any point in time during observations, which is then used to further correct the velocities retrieved:

$$v'_i = v_i - v_{i,trend} \quad (5)$$

where each relative Doppler retrieval  $v_i$  is subtracted by the value of the drift trend  $v_{i,trend}$  at the time  $v_i$  was observed, obtaining the spectral-drift-corrected velocity  $v'_i$ .

### 3.1.3. Error Estimation

The total error on a given velocity measurement  $w_{i,c}$  is the sum of several uncertainties that have different origins. The spectral calibration performed using the Th-Ar lamp can be subject to uncertainties regarding the dispersion spectrum from the lamp itself, the least-square deconvolution of Fraunhofer lines, the additional fit to telluric lines and the unpredictability of weather conditions as well as minor variations in temperature and the pressure of the spectrograph, and guiding and pointing accuracy can all have uncertainties, which affect the Doppler shifts measured that will be used to compute the velocity of the winds on Jupiter. Since the multiple referenced sources have errors of varying degree and we repeat exposures on the same point in the disk as part of our observing routine, it is possible to test the internal consistency of the retrieved radial velocity ( $h$ ) instead of estimating upper limits for each source of error. An estimate of the individual error on each velocity retrieved was made by calculating the standard deviation between two 60 s exposures for each point. Depending on the instrument and the observing time available, more exposures are usually preferred to ensure the consistency of the acquisition process. The velocities on each target point were obtained by weight averaging the retrieved values from consecutive exposures. Taking  $\sigma_i$  as the error on the reference point velocity relative to the retrieval  $v_i$ , the statistical combined error for each point can be calculated using:

$$\sigma'_i = \sqrt{\sigma_{i,trend}^2 + \sigma_i^2} \quad (6)$$

where  $\sigma_{i,trend}$  represents the linearly interpolated error from the deviations of  $v_i$  from  $v_{i,trend}$  along the segment between two reference point exposures. The errors calculated for our Doppler velocimetry measurements with ESPRESSO, taking into account all the factors considered above, were on average 10.6 m/s, with the largest error bar being around 19.3 m/s. Even though all previously mentioned sources of error are important for the precision of the results obtained with this method, the error associated with the pointing accuracy of the fibre's FOV during an exposure was at least one order of magnitude higher than all other contributors to the general error since this error will be propagated through the de-projection of line-of-sight drifts into wind velocities of both zonal and meridional components. To monitor these fluctuations, the observer has the responsibility to control the fibre's FOV drift, verifying if it wanders by more than half the fibre's angular diameter from the targeted point. Should it do so, the observation is discarded and then repeated, a process that is limited by the total allocated time for the observation with the telescope. For the case of ESPRESSO, two 60 s exposures were enough to guarantee a good S/N ratio, while the stability of this state-of-the-art instrument allowed such exposures to be made with confidence.

## 4. Results

### *Doppler Winds with VLT/ESPRESSO*

The results presented in this section constitute a first-time retrieval of atmospheric winds in Solar System planets by ESPRESSO. Thus, given the exploratory nature of this work, we regard these as the first step to fine-tune our model of observation and techniques for the next generation of instruments and telescopes.

With our observing strategy and posterior data reduction and corrections, we were able to retrieve multiple longitudinal profiles of the zonal component of the winds in Jupiter at selected bands signaling the distinct flow regimes.

The changing zonal flow direction and magnitude on equatorial latitudes (20° N–20° S) is readily apparent with our results shown in Table 4. The values presented form an average of the Doppler winds retrieved at each latitude band.

**Table 4.** Averaged Doppler winds on each latitude band observed with VLT/ESPRESSO.

| (1)<br>Latitude (°) | (2)<br>Doppler Wind (m.s <sup>−1</sup> ) | (3)<br>Error (m.s <sup>−1</sup> ) |
|---------------------|------------------------------------------|-----------------------------------|
| 0                   | 119.30                                   | 9.07                              |
| 10                  | 99.43                                    | 10.1                              |
| −10                 | 52.49                                    | 6.65                              |
| 15                  | −16.8                                    | 9.17                              |
| −15                 | −18.4                                    | 13.36                             |
| −21                 | 33.2                                     | 16.3                              |

(1) Observed latitude band; (2) zonal wind speed calculated from Doppler velocimetry technique; (3) average error of measurements in its corresponding latitudinal band. Negative values of the zonal wind indicate westward flow.

Figure 2 shows the wind velocity values retrieved along each band for each position observed with ESPRESSO. For this observing run, the winds are stable within the error bars of the retrieved data; however, in the observations at 10 degrees North, we see increased variability in the same latitudinal band.

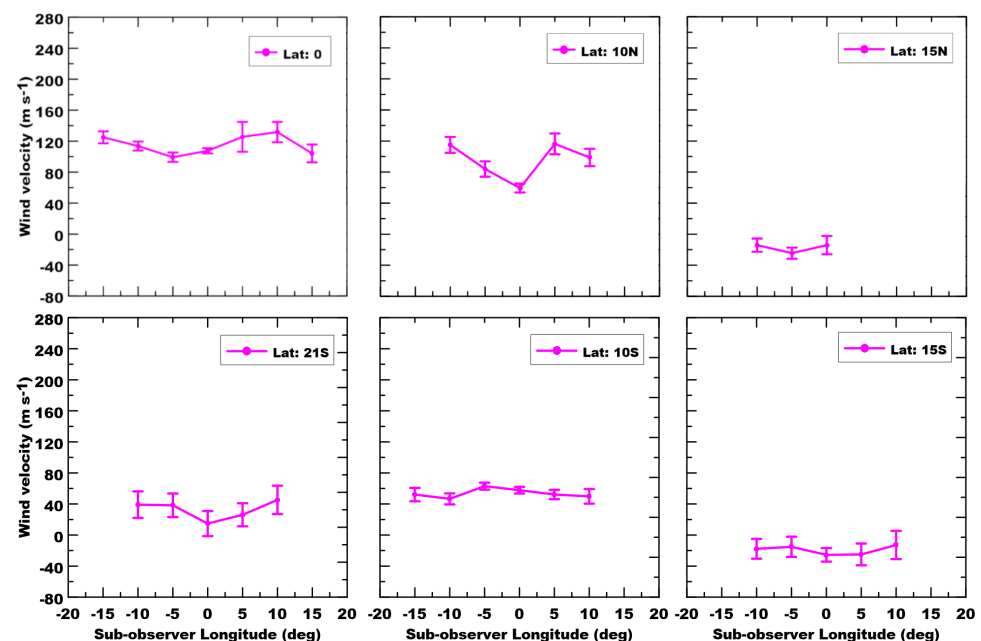


**Figure 2.** Zonal wind in each band of Jupiter with observations from VLT/ESPRESSO. The longitude in these plots has the sub-observer longitude as the reference point; hence, it is not the true planetary longitude.

## 5. Comparison with Previous Measurements

### 5.1. Cloud Tracking

Given the general stability of the zonal wind profile of Jupiter, we can compare our Doppler velocimetry retrievals with previous results, even if the observations are separated by a number of years. However, some caution must be taken since, although the general variability in the wind profile stays at the order of 10 m/s, which is comparable to our error bars, episodes of increased variability have been observed [31]. The magnitude of the jets

at approximately  $7^{\circ}$  S and  $6^{\circ}$  N, and  $24^{\circ}$  has been noticed to change by more than 40 m/s at specific periods of observation [11,17,19].

The general stability of the zonal wind profile of Jupiter between 30 degrees south to 30 degrees north can be verified in Figure 3. This plot also highlights the periods of variability at specific regions on Jupiter's banded circulation, especially for the Hubble Space Telescope observations, which are spread over a larger time scale. Several authors have explored the causes for these changes [14,16,31], mentioning that the time intervals for these variations can range from hours to months, making it difficult to determine the average zonal wind profile and the exact culprit of many of these changes [31]. For all measurements in Figure 3, a cloud-tracking method was employed even if several techniques from individual [14] and automatic tracking [13] to 2D correlation routines [9,10] were used.

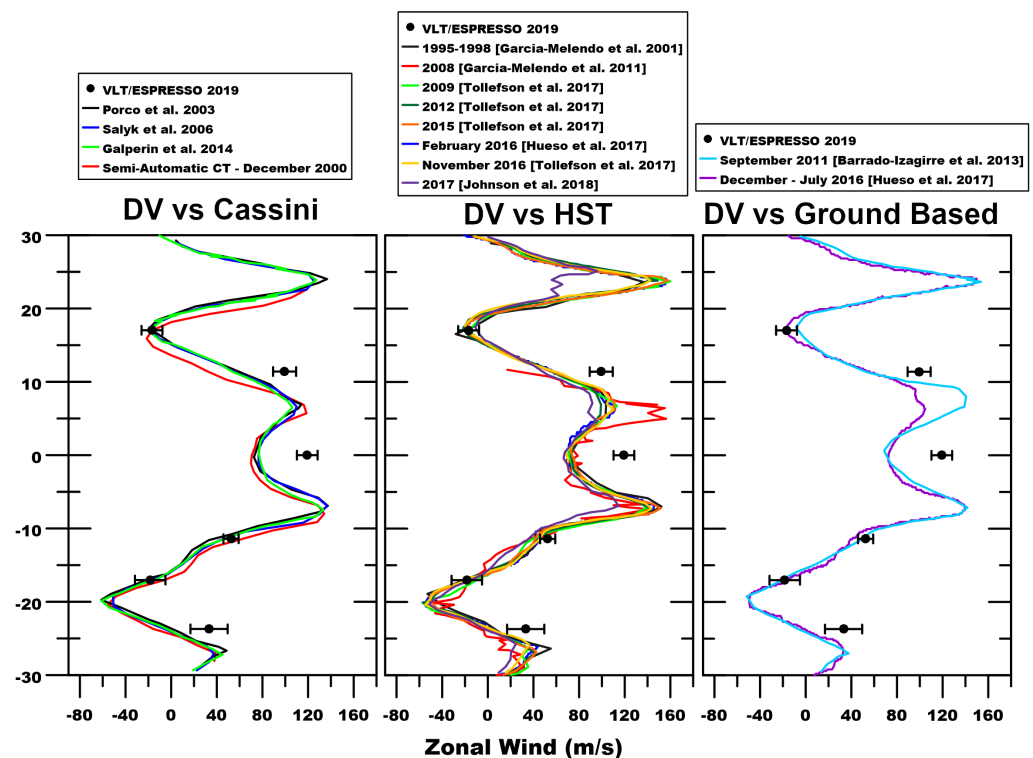


**Figure 3.** Comparative wind profiles retrieved from Cassini, HST and ground-based observations with Doppler velocimetry results at visible wavelengths. Error bar values represent  $1\sigma$  error. We limit the profiles to equatorial latitudes to match the range of our ESPRESSO observations. Each of the wind profiles used for comparison is taken from a previous publication with the exception of the red profile in the leftmost panel. These are wind velocity results retrieved with 2D semi-automatic correlation cloud-tracking using the PLIA tool [41].

We can see our Doppler velocimetry results compared with retrieved wind velocities from different instruments in Figure 3. The Cassini profiles feature reference data from automatic cloud tracking from two separate authors [12,13], and an additional analysis using 2D correlation of mosaics built with Cassini/ISS images during the fly-by period between December and January 2000/2001 [10]. For completion, we present an additional wind profile with cloud-tracking results using a semi-automatic method, on which we targeted similar latitudes that were observed with ESPRESSO. Even though the data from this cloud-tracking routine are approximately 20 years apart from our Doppler wind retrievals, such a comparison is still useful to evaluate the profile's evolution through time.

The middle panel features more profiles due to the higher cadence of observations provided by HST, including an effort to continuously provide imaging data on Jupiter's atmosphere to accompany its evolving atmosphere, through the OPAL program that

started observations in 2014 [42] on Uranus and 2015 on Jupiter [43]. The record of HST observations in Figure 3 starts in 1995 with the study by [14] who did not report any significant changes in the zonal wind profile during their period of observation. The next set of observations occurs with [11], which coupled observations from both Cassini and HST in 2008, reporting an increase on the  $6^\circ$  N jet by approximately 40 m/s. We include then a more extensive report of HST observations in [16] featuring Hubble data from 2009–2016 and another observation in 2016 by [15], which was accompanied by ground-based observations. The last set of data from 2017 was explored in [17], who also analysed the zonal wind profile of Jupiter with different filters from HST.

The rightmost panel in Figure 3 shows ground-based measurements taken from observations with the Pic du Midi 1 m telescope [19] and a collection of different observations from amateur astronomers and PlanetCam UPV/EHU [44] mounted on the 2.2 m telescope in Calar Alto Observatory [15].

From the three profiles, we can verify that there is reasonable agreement between our Doppler retrievals and previous results within 30 degrees south and north of the equator. However, it is interesting to note that at the equator,  $0^\circ$  latitude, the Doppler winds appear to be faster than any previous measurements, by a difference that exceeds 20 m/s, double what local and temporal variations in the zonal wind predict. It is possible that this value represents the velocity of atmospheric particles at a slightly different pressure level than what is retrieved with cloud tracking. Given the exploratory nature of this work, and thus the lack of more substantial data, it is difficult to confirm this for the time being.

## 5.2. Previous Doppler Velocimetry Results

Since this work explores the capabilities of ESPRESSO to perform Doppler velocimetry on planetary atmospheres of the Solar System, the volume of data of this kind to compare with our observations is relatively scarce as opposed to cloud tracking. Multiple studies [25–27,29,37,38] have used Doppler velocimetry to retrieve winds on Venus at visible wavelengths, and other targets have been considered with similar techniques such as Mars at sub-mm/mm wavelengths [45,46] and Titan in the infrared range [47–50].

Doppler velocimetry on Jupiter at similar wavelengths to this work was achieved with success for the first time in [21] with JOVIAL–JIVE (Jovian Oscillations through Velocity Images At several Longitudes–Jovian Interiors from Velocimetry Experiment in New Mexico) observations in 2015 and 2016.

A comparison between the Doppler winds retrieved for this work and previous measurements with a similar technique is presented in Figure 4. Even though both techniques use visible solar light reflected on Jupiter’s upper tropospheric clouds, and the time separation between observations is not large when looking at previous comparisons with cloud-tracked winds, there is some discrepancy between both data sets. Although there is good agreement at  $10^\circ$  S and  $15^\circ$  S, our other average values differ from the profiles retrieved by [21] by 5–6  $\sigma$  (the error bar of our retrievals) when taking into account the other data points. Since this method measures the actual velocity of atmospheric particles, Doppler winds can be subject to variations due to wave activity [21], which can translate to higher magnitude differences than the previously mentioned 10 m/s. However, when comparing our results with observations with HST in 2015 and 2016 (see Figure 3), which [21] used for comparison in their Doppler velocimetry results, we do not find such significant differences. It is true that this work is exploratory and it features a single observing run, but ESPRESSO has an overall higher spectral resolution than the instrument used in [21], which can be an alternate explanation, as ESPRESSO results should be more sensitive to the alternating jets of Jupiter.

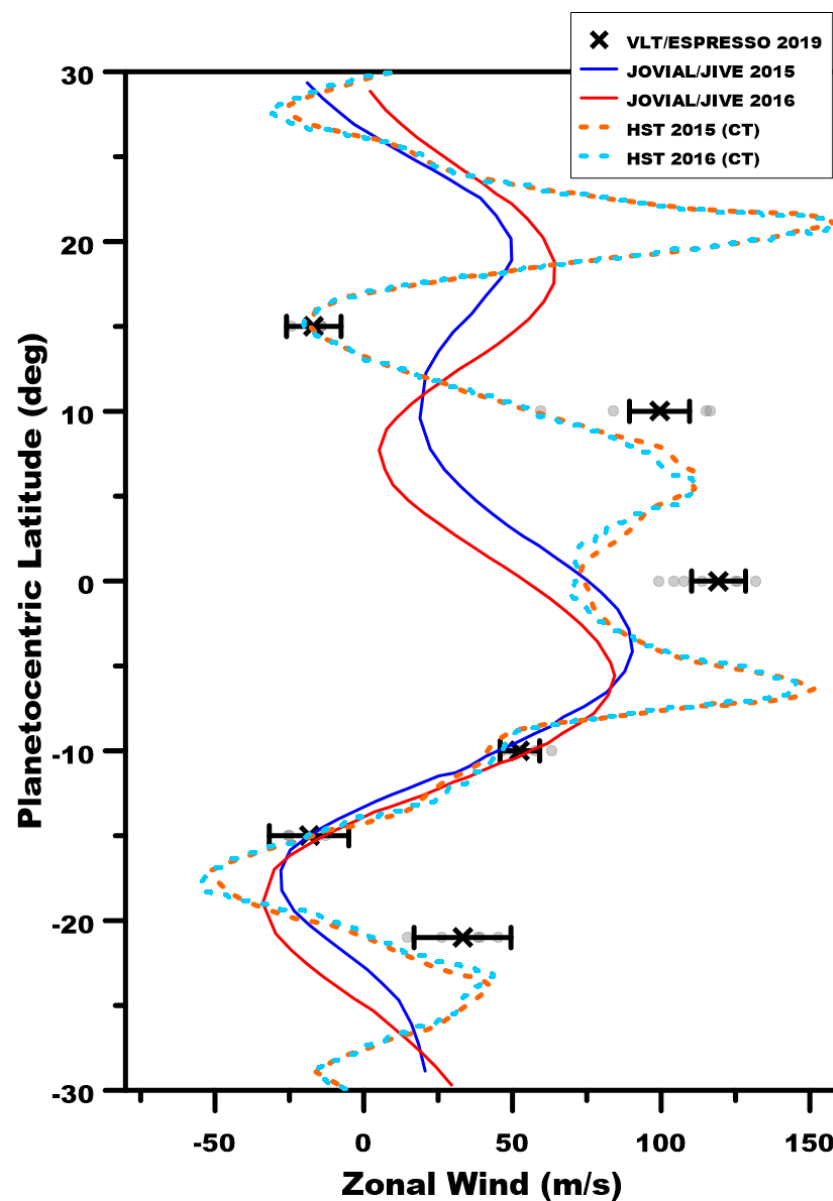


**Figure 4.** Zonal winds retrieved with Doppler velocimetry techniques with VLT/ESPRESSO observations (calculated average—black crosses) and the JOVIAL–JIVE retrievals in 2015 (blue profile) and 2016 (red profile). The faint gray circles are the data points of our Doppler wind retrievals from which the average was calculated, whose values are presented in Table 4. We also present here cloud-tracking results from HST data in 2015 [16] and 2016 [15] as orange and light blue dashed lines, respectively.

### 5.3. Multiwavelength Comparison

Since ESPRESSO observations, for the purpose of this work, were performed using the full set of Fraunhofer lines in the visible part of the spectrum, it is possible that the winds retrieved with our Doppler method originate from different regions of the troposphere than the visible cloud layer observed previously with Cassini or HST. In [17], they employ a multiwavelength analysis of Jupiter’s banded structure to study the zonal wind profile’s variation as a function of wavelength.

In Figure 5, we present the zonal wind profile at multiwavelengths in both ultraviolet [51] and visible wavelengths [17] to compare with our Doppler results. The profile remains mostly unchanged at visible wavelengths (395–658 nm), except at the two most powerful jets at approximately 7° S and 23° N, which seem more sensitive to different wavelengths. Moreover, most cloud features that are identified with cloud-tracking tech-

niques are present on most visible wavelength filters with little changes in morphology or drift rate [51]; hence, the stability of the zonal wind profile across several wavelengths is also in part a consequence of the relatively large vertical structure of most tracked features. The wind profile retrieved in the ultraviolet (264 nm) tracked features that could not be observed at other wavelengths was similar to the ones discussed in [17]. These higher winds at approximately 350 mbar pressure level [6] appear to have less prominent jets across all latitudes and a slight increase in wind magnitude at the equator. However, it is not enough to justify the 110 m/s Doppler wind retrieved at the equator with ESPRESSO.

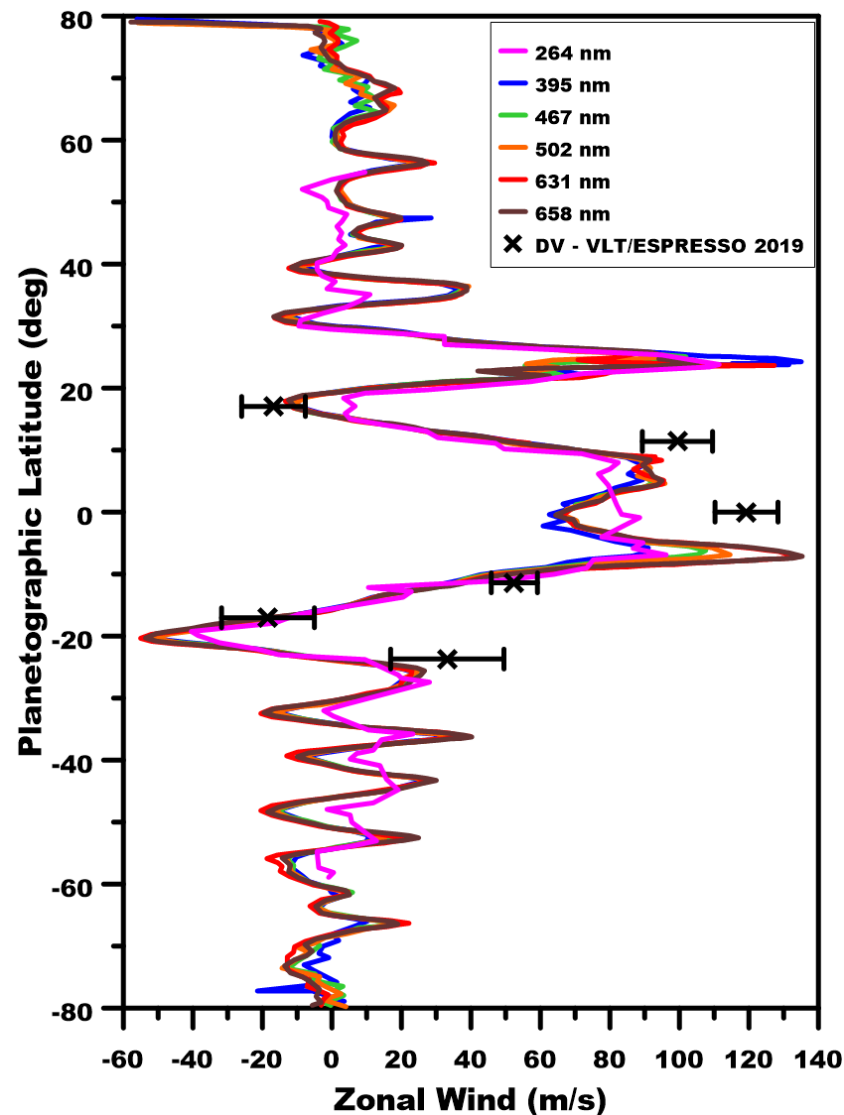


**Figure 5.** A multiwavelength analysis of the zonal wind profile on Jupiter at visible and ultraviolet wavelengths to compare with the Doppler winds retrieved with VLT/ESPRESSO. The ultraviolet profile from [51] is the result of cloud tracking of higher altitude features than what is identified at visible wavelengths at 0.7–1.5 bar. The pressure levels associated with features observed at visible and UV wavelengths are at approximate altitudes from −14 to 9 km and 25 km, respectively, in relation to the reference altitude where the pressure is equal to 1 bar. The other five profiles were all retrieved with HST observations as described in [17].

Longitudinal variations could also explain some of these differences between the results presented in this work and the legacy of zonal wind measurements retrieved, as these can have magnitudes that go beyond the standard deviation of our results as reported in [17].

### Considerations on Altitude of Wind Velocity Tracers

Even though wind results from both our Doppler technique and cloud-tracking seem consistent, there are important differences in how these velocities are retrieved. This can have implications for their interpretation and vertical location in the atmosphere [37]. The cloud-tracking method follows the movement of cloud features in the atmosphere. As such, the altitude/pressure level from which winds are extracted is directly dependent on where these features are formed and propagate, which for the case of Jupiter is roughly at the 0.7–1.5 bar level [2,6]. The Doppler velocimetry method used in this work relies on backscattered sunlight dispersed from Jupiter's atmosphere. The spectra obtained by ground-based observers is the result of a bolometric integration of this backscattered radiation towards the observing line-of-sight. Although mostly concentrated on the region where optical depth reaches unity, which is roughly where the cloud features can form in the upper troposphere [12,31], it is possible that the average radiation that arrives at the instrument's detector could include scattering from slightly higher levels. For this reason, it is reasonable to expect some fluctuations in the results from both techniques. A more extensive observing campaign of Jupiter with high-resolution spectroscopy, coupled with coordinated observations to perform cloud tracking in a multiwavelength range would allow further exploration of this subject.

Since the Doppler velocimetry method relies on solar light backscattered from Jupiter's dayside atmosphere, the altitude of the retrieved zonal velocities ought to be located where the optical depth reaches unity [37]. Several models for the cloud properties on each band have been developed over the years, which, applied to the bands observed in this study, show that optical thickness unity is reached in the Equatorial Zone at approximately 0.7 bar, and to slightly deeper values for both the North and South Equatorial Belts [52–54]. According to these models, we can be sensing somewhere between the upper part of the cloud layer and a chromophore coating, postulated by [55] to explain the red colouring of Jupiter's Great Red Spot and then expanded by [56] to explain the different colourations of the belts. From this contrast between belts and zones, it is possible that features followed with cloud tracking could be formed at different pressure levels. Although this is out of the scope of this exploratory study, since with our Doppler velocimetry technique we use observations in the visible wavelength range, it is possible that we might be sensing slightly different pressure levels as a function of wavelength. We intend to address these issues in our follow-up research.

#### 5.4. Wind Component Entanglement

Since we are measuring winds from the radial velocity component obtained from backscattered spectra of Jupiter, the resulting wind velocity is the sum of all its components. This method has been used extensively to study Venus [25–27,29,37,38] where the zonal wind dominates atmospheric circulation at the cloud tops. For the case of Jupiter, each band can be understood as its own *Hadley–Walker* circulation cell such that each can have a distinct zonal flow, making meridional flow measurements hard to obtain for each band due to limited spatial resolution from Earth observations [22]. The presence of storms, particularly in the belts, along with a high level of turbulence is evidence of vigorous convection and vertical wind shear in the upper troposphere of Jupiter, which means that the vertical component of wind velocity could be an important contributor to the overall wind velocity retrieved from the Doppler velocimetry method. Hence, there is the possibility that our method is sensitive to additional components of the wind. However, since this study covered a small region over a short time interval in the atmosphere of Jupiter, and consequently has few data points, it is challenging to evaluate the strength of the vertical wind contribution from these results alone.

### 6. Conclusions

In this body of work, we attempted to explore the capabilities of VLT/ESPRESSO in the study of Solar System planets' atmospheres, in this case Jupiter. We adapted and

refined a Doppler velocimetry method to retrieve wind velocities on the upper atmosphere of Jupiter from ground-based telescopes, with heritage from observations of Venus made with different instruments [21,26,27,29,37,38]. This exploratory project shows evidence that Doppler velocimetry applied to visible spectra from backscattered solar radiation from the atmosphere of Jupiter efficiently retrieves wind velocity results along Jupiter's different latitudinal bands. To support this new application of the method, we compared our retrieved Doppler winds with the ones obtained from the analysis of Cassini images of Jupiter taken during its fly-by manoeuvre in December 2000 using the cloud-tracking technique (CT). However, winds derived in this manner (CT) are usually averaged over several days of observations and do not reflect instantaneous wind velocity and its significant variability at shorter time scales. The ground-based Doppler velocimetry technique has proven its reliability in constraining global wind circulation models, complementary of space-based measurements, and we also assessed the feasibility of monitoring Jupiter's atmosphere dynamics and variability on short time scales, from the ground. This work also shows that we can take advantage of ground-based observations, with the extremely high-resolution spectroscopic capabilities of VLT/ESPRESSO, for studying the spatial variability of winds and the presence of storms in Jupiter's troposphere.

In spite of the limited spatial and temporal coverage of Jupiter's disk allowed by the allocated observations, our results show general consistency with winds retrieved by cloud tracking. Furthermore, results from both cloud tracking and Doppler velocimetry are also consistent with reference results from various papers that represent a diverse study of the upper troposphere of Jupiter with different instruments from Cassini and HST [12,15]. Given that pointing accuracy is the most important source of error for Doppler wind results, there is the possibility that the ESPRESSO observations are skewed by a few arc seconds, which in some cases, might be enough to significantly alter the wind measurements retrieved due to the steep wind velocity difference between some bands since and also the fact that some of these latitudes stand at the cusp between zones and belts. Although seeing conditions during the observing run were optimal (1.25 maximum), it might be enough to influence pointing accuracy at the scale of belt/zone transitions [22].

Since this study shows that the Doppler velocimetry technique, using high-resolution spectroscopy and ground-based observations, performs effective dynamical atmospheric studies on Jupiter, and despite the aforementioned consistency between the results with other techniques using space-based observations, we do see slight fluctuations in some of the bands studied with both methods that are also reported here, and for which tentative hypotheses for their origin are suggested. However, given the exploratory nature of this work, our coverage was limited; thus, no firm conclusions could be made regarding the differences in wind velocities retrieved between both methods. With the observed general agreement between the results, in the future, we intend to perform a wider observational study to cover a broader region of Jupiter with the possibility to analyse more elements of the banded structure of its atmosphere and greater temporal coverage. This would not only extract winds during a full rotation period but also allow for investigation of temporal daily variability.

Since we sense the overall visible wavelength range with the Doppler velocimetry technique and since optical depth is a function of wavelength, it is possible to explore the use of partial wavelength ranges in order to sense different pressure levels/altitudes simultaneously. To confirm the location of pressure levels probed with such a study, we plan to employ a modern radiative transfer suite, such as NEMESIS [57]. Such observations, coupled with cloud-tracking results, could allow us to estimate the vertical shear of the zonal wind in the upper troposphere where a transition between circulation regimes might be occurring [1]. We have prospects of using this technique for future dynamical studies of planetary atmospheres on other giant planets in the Solar System. Saturn is our next target, and we plan to conduct a dynamical study of its atmosphere throughout 2024. For the ice giants, Uranus and Neptune, we intend to explore the future observational capabilities of the Extremely Large Telescope (ELT), with its enhanced spatial resolution and spectral

precision of the ANDES spectrograph. With the advent of this exceptional observational facility and its telescope–spectrograph combination (ELT-ANDES), we are confident about easily adapting our technique to study the atmospheric dynamics of Uranus and Neptune in depth.

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**Data Availability Statement:** The data are available in a publicly accessible repository. The data presented in this study are openly available in Machado, Pedro (2023), “Dataset23\_Jupiter\_PMachado”, Mendeley Data, V1, <http://doi.org/10.17632/7smfyv5y53.1> (accessed on 15 November 2023).

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**Conflicts of Interest:** The authors declare no conflict of interest.

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