Characterization of Venus' cloud top dynamics using ground-based Doppler velocimetry

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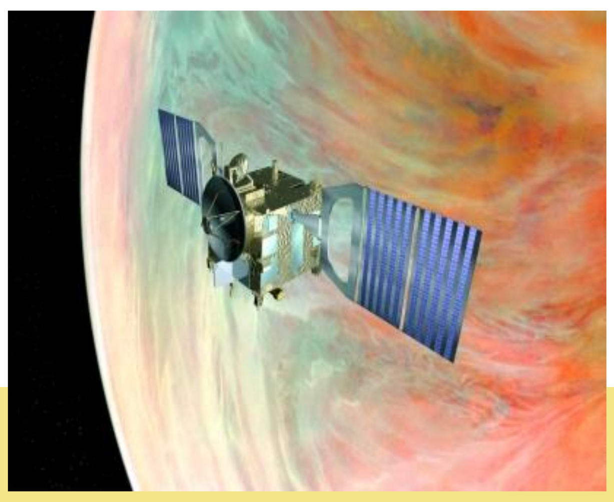
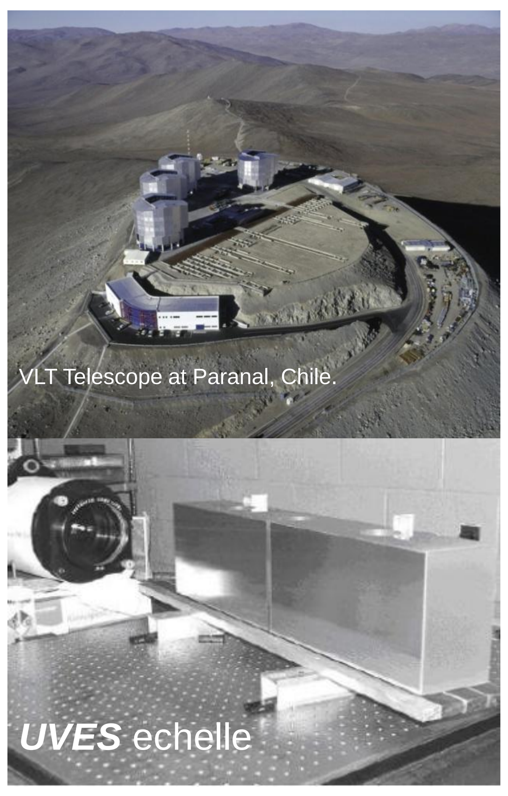


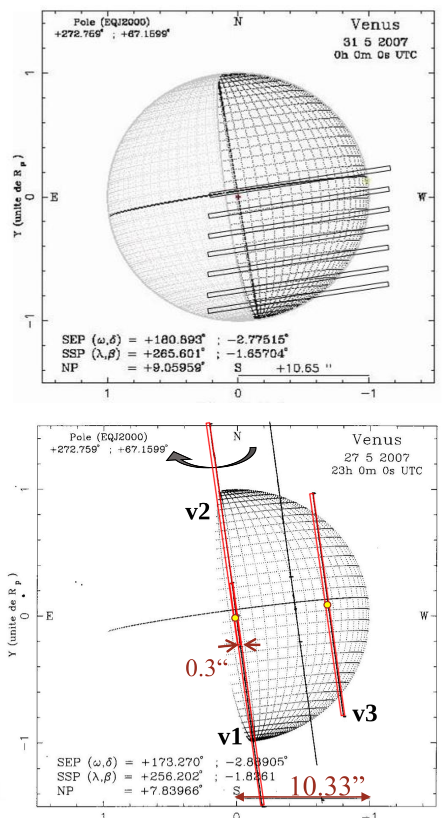
Context

In the context of the Venus-Express mission, the zonal circulation at the cloud tops has been subject to an intense scrutiny both from the spacecraft instruments (VIRTIS, e. g. Sanchez-Lavega et al. 2008 ; VMC, e. g. Moissl et al. 2009) and ground-based observations (Widemann et al., 2008, Gaulme et al., 2008, Gabsi et al., 2008).

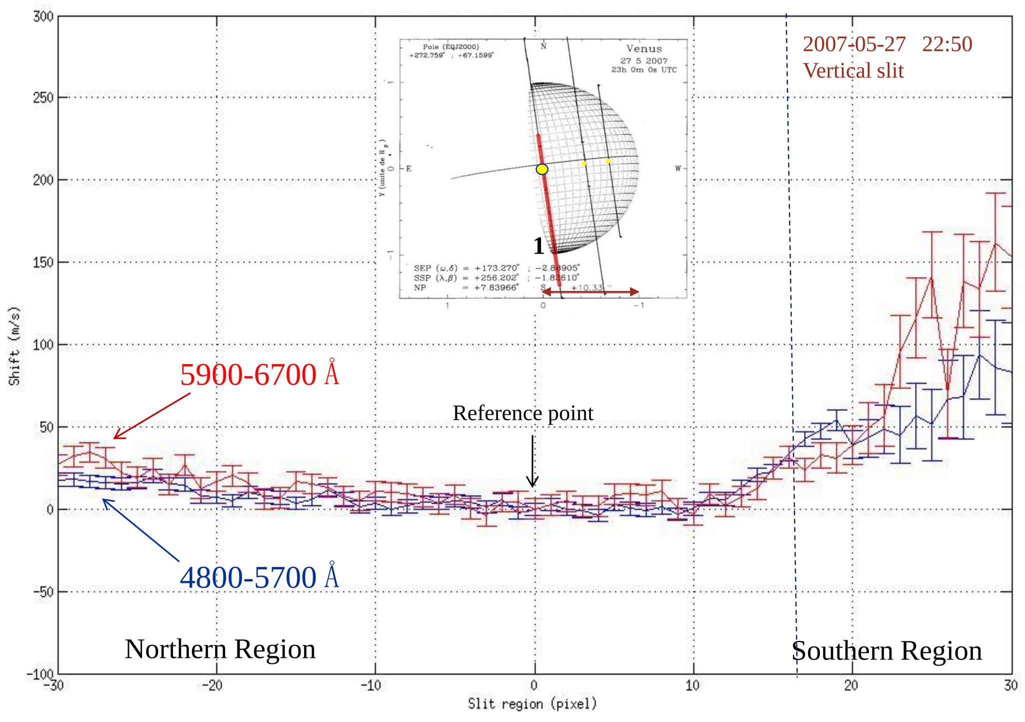
The retrograde, zonal super-rotation of the atmosphere of Venus was traced back to Mariner 10 data [Limaye and Suomi, 1981], Pioneer Venus and Galileo SSI [Rossow et al., 1990; Belton et al., 1991, Toigo et al. 1994; Limaye 2007; Peralta et al., 2007]. VMC and VIRTIS measurements by cloud tracking show a high dispersion of the instantaneous direct measurements of the wind, as well as variability with local time, and time-dependency of the mid-latitude jet.

In the lower mesosphere (65-85 km), visible observations of Doppler shifts in solar Fraunhofer lines have provided the only direct Doppler wind measurements near the cloud tops in recent years (Widemann et al., 2007). The main purpose of our work is therefore to provide direct wind measurements using visible Fraunhofer lines scattered by Venus' cloud tops, and study their spatial and temporal variation scales.

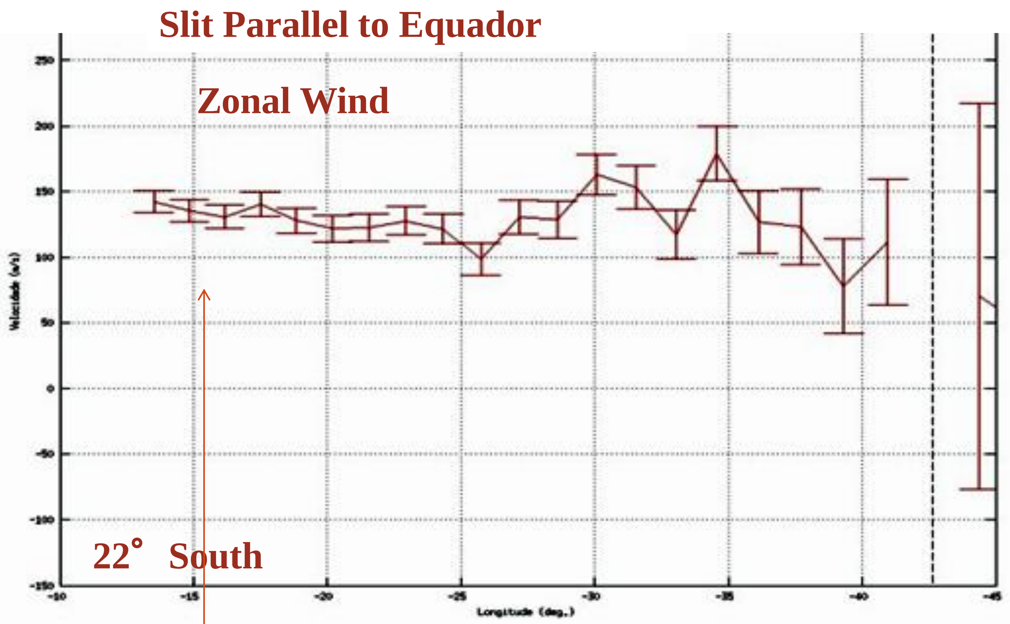


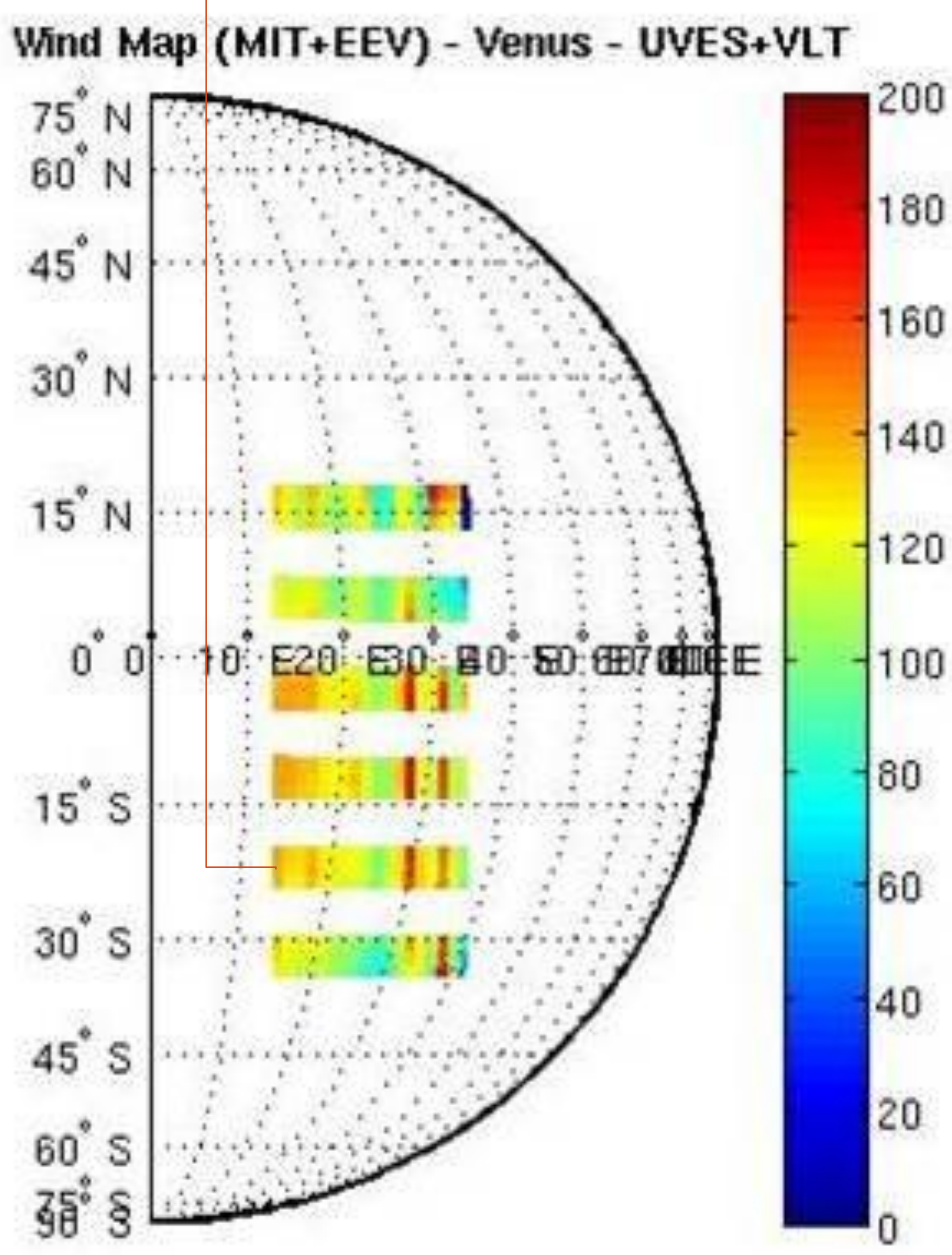


Example of relative Doppler shift curve

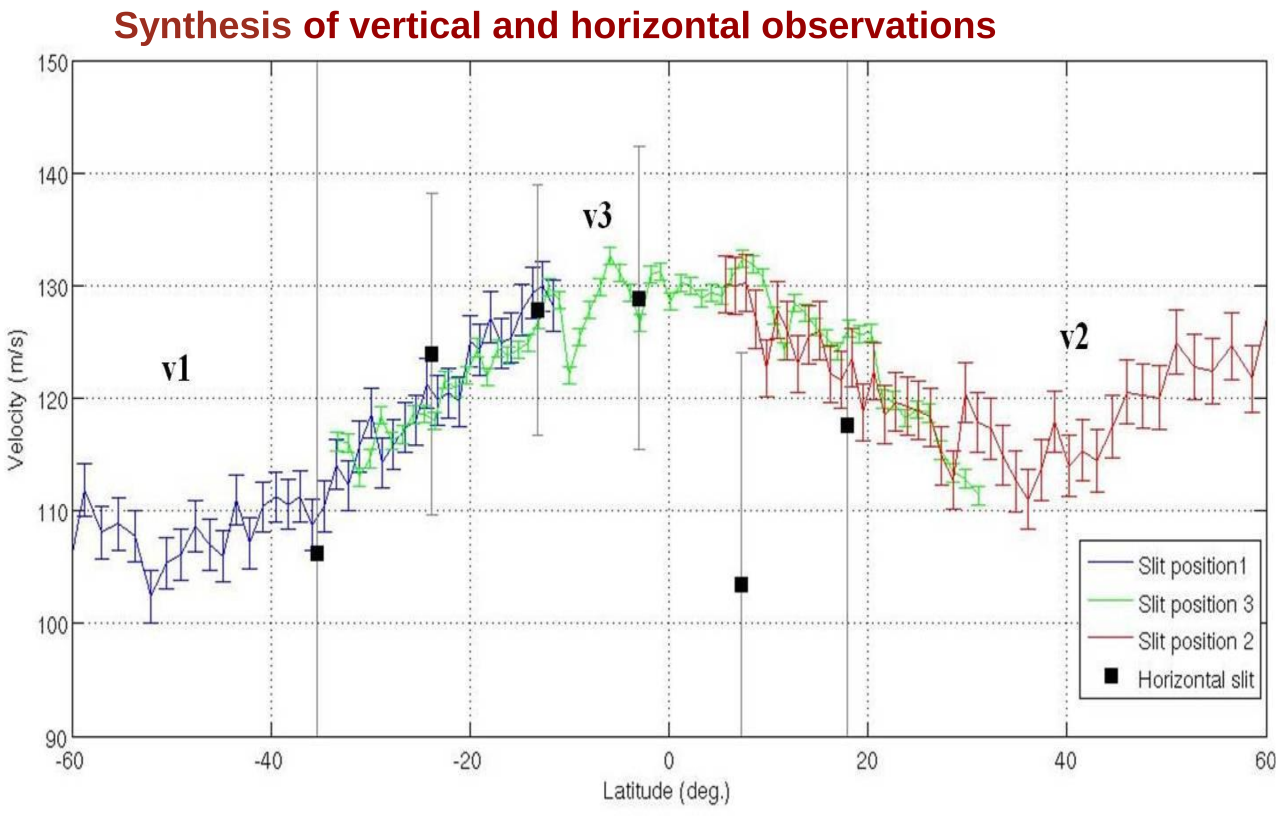


Slit Parallel to Equador





Synthesis of vertical and horizontal observations



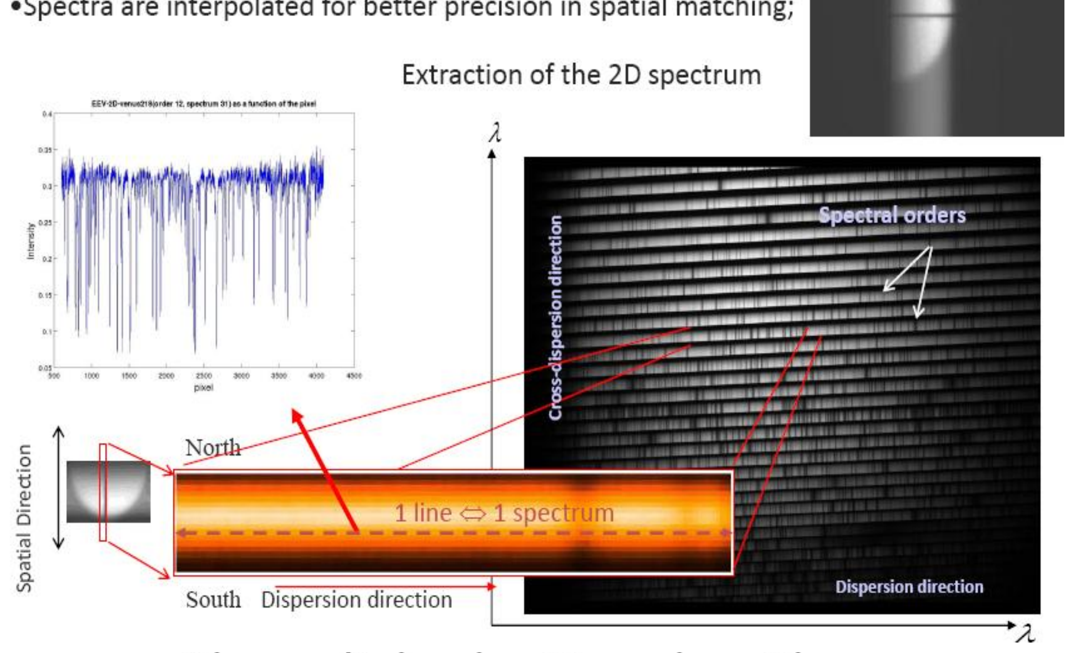
Summary of results

- The wind map obtained, displays the spatial variation at six latitudes between 15° N and 30° S, at local solar times varying between 15h and 18h. It shows that the velocity tends to be higher at lower latitudes, with a variation on the order of 30 m/s between the equator and 30° S. Longitudinally, in general the wind increases at higher local solar times. However, some fine structure is present between 25° and 40° longitude.

- In the figure with the slit parallel to the rotation axis, the absolute velocity measurements are plotted together with the relative velocity curves derived from observations with slit positions v1 to v3. The curves from horizontal observations have been averaged in longitude and are shown as black squares. Relative velocities from positions v1 to v3 are shown for comparison. The relative velocities are in good agreement with the absolute velocity measurements and indicate the same general behavior: a decrease on the order of 20 m/s between the equator and the midlatitudes, with a slight asymmetry between the northern and southern hemispheres (on the order of 5-10 m/s).

Analysis procedure

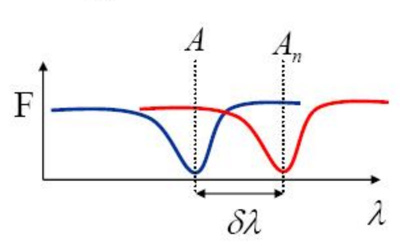
- Echelle orders are extracted and analyzed separately;
- Spectra are interpolated for better precision in spatial matching;



The radial velocities algorithm

1) One line:

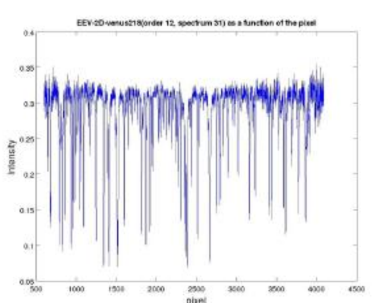
$$\frac{\delta V_n}{c} = \frac{\delta\lambda}{\lambda}, \quad A_n - A \approx \frac{\partial A}{\partial \lambda}\delta\lambda \;\Rightarrow\; \frac{\delta V_n}{c} = \frac{A_n - A}{\lambda \frac{\partial A}{\partial \lambda}}$$



2) full spectrum or spectral order:

$$\Delta V = \frac{\sum \frac{\delta V_n}{\sigma^2(\delta V_n)}}{\sum \frac{1}{\sigma^2(\delta V_n)}} \qquad M(\lambda) = \frac{\lambda}{A_n}\frac{\partial A}{\partial \lambda}$$

$$\frac{\Delta V}{c} = \frac{\sum (A_n(\lambda) - A(\lambda)) M(\lambda)}{\sum \lambda \frac{\partial A}{\partial \lambda} M(\lambda)}$$

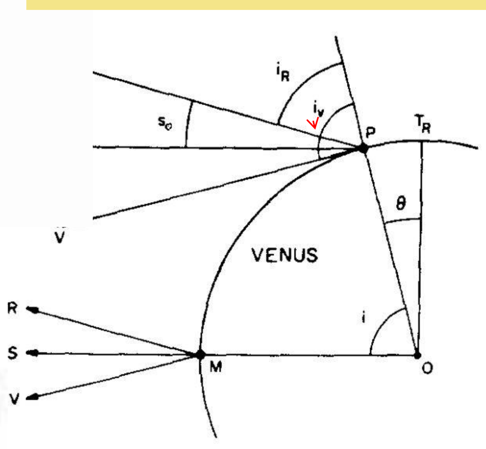


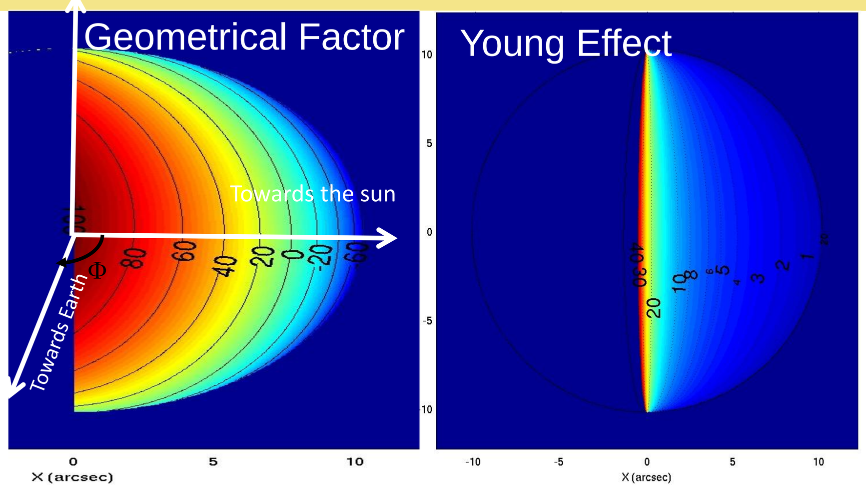
[Connes, P. (1985), Astroph. & Sp. Sci., 110, 198]

Method

The methods developed in recent planetary wind measurements in the visible range using high-resolution spectroscopy (Civeit et al., 2005; Luz et al., 2005, 2006; Widemann et al., 2007, 2008) address the fundamental problem of maintaining a stable velocity reference. There are systematic errors involved in trying to measure absolute wavelengths or Doppler shifts with grating spectrographs. At high spectral resolution, the dispersion law cannot be considered an absolute velocity frame (due to instrumental uncertainties) with an absolute accuracy better than about 90-100 m/s, while in measuring the global wind circulation at cloud tops, we are addressing wind amplitude variations (or wind latitudinal gradients) on the order of 5-10 m/s (Widemann et al., 2007) projected on the line-of-sight. It is therefore necessary to measure relative Doppler shifts between two sets of absorption lines.

We used the technique of Doppler velocimetry (Connes 1985) of the Fraunhofer lines (visible) obtained with VLT + UVES (R~100 000). This technique allows to determine wind speeds on the order of some m/s. The spectrograph probes the visible radiation scattered by the top of the cloud layer, where $\tau \sim 1$.





The Doppler shift is produced by the method of Connes in the form of a differential velocity (relative to a reference spectrum). There are two factors which affect the measurement of the zonal winds. They are the **geometric factor** (F) and the **Young effect** (Y). Overall: $\Delta V = F\,V + Y$.

Young Effect -Young (1975) discussed a further systematic effect affecting the solar Fraunhofer lines, caused by the angular size of the Sun and its rapid rotation. Points near the terminator of Venus are unequally illuminated by the approaching and receding limbs of the rotating Sun. As a consequence, average solar illumination is apparently shifted due to missing radiation. This effect is of the order of the Sun's equatorial velocity (2 km s^{-1}), multiplied by the ratio of its apparent angular radius as seen from Venus, to the angular distance from the target point to the terminator.

$Y = 3.2 \tan(SZA)$, where SZA is the sun's zenith angle.

Geometric Correction Factor

$$\Delta V = F\,.V = V.2\cos(\varphi/2)\cos(\varphi - \Phi/2)\cos\beta$$

where Φ is the phase angle, β is the sub-Earth point latitude and φ is the longitude.

Discussion and conclusions

- The upper cloud layer is located at about 70 km altitude (Ignatiev et al., 2009), which corresponds to the maximum speed of zonal super rotation. The method allowed us to characterize the spatial variations of zonal wind as a function of latitude (the slit is thin compared to the size of the disk image of Venus).
- The Doppler velocimetry technique (absolute accelerometry) used allowed a data reduction with an accuracy in the obtained wind velocities on the order of 10 m/s.
- The zonal wind magnitudes obtained are in general consistent with the ones obtained by Galileo SSI, VMC, VIRTIS.
- In the case of the slit perpendicular to the axis of rotation was possible to determine the absolute value of the zonal wind for the latitudes surveyed, by assuming a uniform zonal velocity along parallels. This is, currently, the only technique that can derive the absolute wind's velocity value, and with a high spatial resolution. Both short-term variations and small scale structures can be studied. The latitudinal dependence of the zonal wind at cloud level and the existence of wave patterns can be investigated, and correlated with winds determined from cloud tracking in the VEx VIRTIS-M and VMC UV images.
- A new set of recent data taken at CFHT/ESPaDOnS in February 2011, in coordination with Vex/VMC measurements, will help pursue our program of monitoring the wind variability and wave structure at cloud tops.

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