Ground and Space based cloud-top wind velocities using CFHT/ESPaDOnS (Doppler velocimetry) and VEx/VIRTIS (cloud tracking) coordinated measurements

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Context

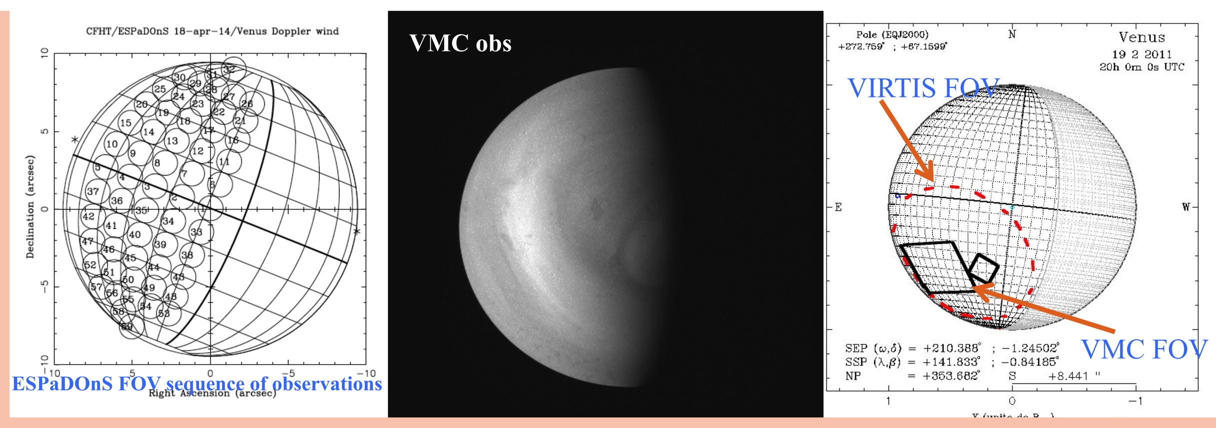
Since the Venus Express spacecraft operations started in 2006, a continuous effort has been made to coordinate its operations with observations from the ground using various techniques and spectral domains (Lellouch and Witasse, 2008).

A complete characterization of the venusian superrotation is crucial for understanding its driving mechanisms. In the lower mesosphere (65-85 km), visible observations of Doppler shifts in solar Fraunhofer lines have provided the only Doppler wind measurements near the cloud tops in recent years (Widemann et al., 2007, 2008, Machado et al., 2012, 2014). The region is important as it constrains the global mesospheric circulation in which zonal winds generally decrease with height while thermospheric subsolar–antisolar (SS-AS) winds increase (Bougher et al., 1997; Lellouch et al., 1997).

Renewed interest on measuring the winds at clouds top from the ground has emerged in the course of the Venus Express mission as well as reanalysis of Galileo observations (Limaye, 2007; Peralta et al., 2007). On Venus-Express, atmospheric circulation at 70 km (and as well near 50 km) is being measured from cloud tracking by both VIRTIS-M and VMC (Markiewicz et al. 2007, Peralta et al. 2007, Luz et al., 2011, Peralta et al., 2012).

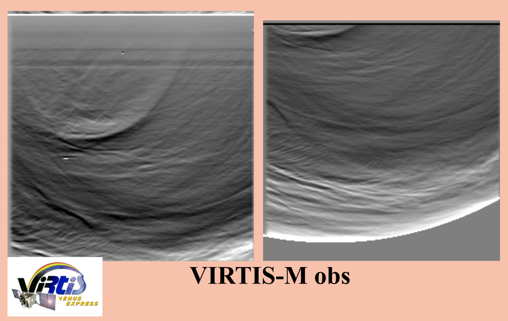
Our main purpose is to provide direct wind measurements using visible Fraunhofer lines scattered at Venus' cloud tops. This will also contribute for cross validation of both methods, the Doppler wind velocimetry and the cloud tracking method, which measure winds independently.

We use observations from 16-21 Apr 2014 taken with the 3.60-m Canada-France-Hawaii telescope (CFHT) Visible Spectrograph **ESPaDOnS**, and compare results with coordinated observations from Venus Express VIRTIS instrument.



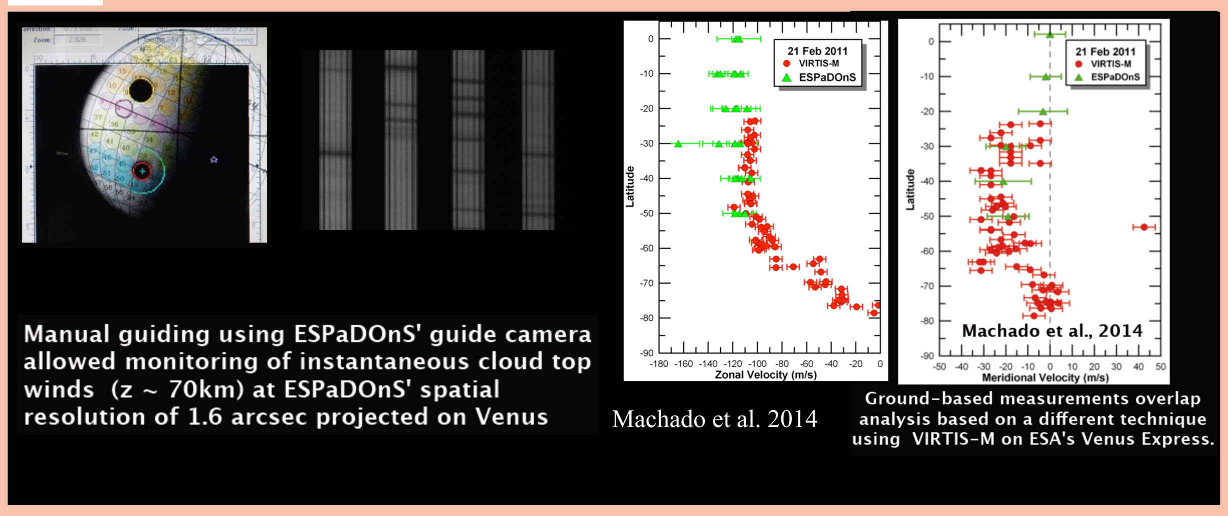
Coordinated 2014 observations at CFHT and Venus Express

•High-resolution spectra of Fraunhofer lines in the visible range (0.37–1.05 μm).
•Made at 16-21 February 2014 and were coordinated with VMC and VIRTIS-M observations from ESA's Venus Express (VEx) mission.
•The complete optical spectrum was collected over 40 spectral orders at each point with 2-5 seconds exposures, at a resolution of about 80000.
•Various points of the dayside hemisphere at a phase angle of 67 degrees, between +70 and -70°by steps of 10°in latitude, and +70°to -12°to sub-Earth meridian in longitude by steps of 12°.



VIRTIS-M obs

16 April 2014: orbit 2918 (data VMC and VIRTIS-M)
17 April 2014: orbit 2919 (only VMC)
18 April 2014: orbit 2920 (only VMC)
19 April 2014: orbit 2921 (only VMC)
20 April 2014: orbit 2922 (only VMC)
21 April 2014: orbit 2923 (data VMC eandVIRTIS-M)



Method

➢The Doppler shift measured in solar scattered light on Venus' dayside results from two instantaneous motions : (1) a motion between the Sun and Venus' upper cloud particles ; this shift is minimal near Venus sub-solar point ; (2) a motion between the observer and Venus' clouds ; this effect is minimal at the sub-terrestrial point.

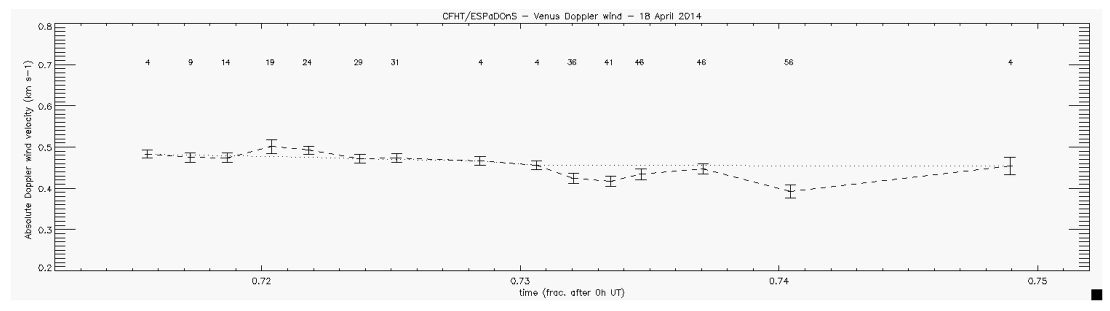
➢Methods applied in recent planetary wind measurements using high-resolution spectroscopy in the visible range (Luz et al., 2005a, 2006; Widemann et al., 2007; Gabsi et al., 2008; Widemann et al., 2008, Machado et al. 2014) all address the fundamental problem of maintaining a stable velocity reference.

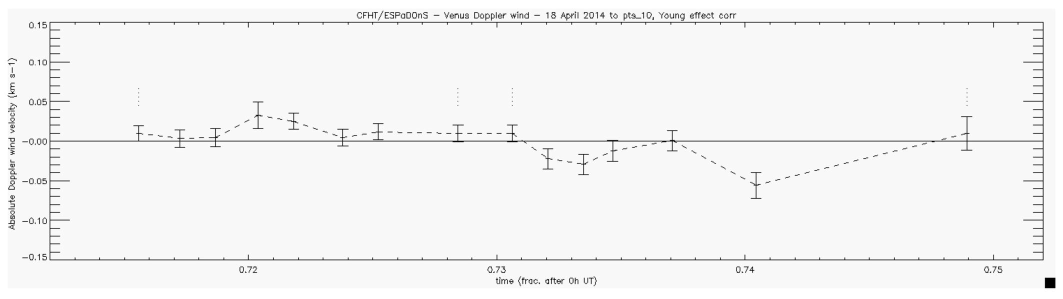
➢We need to address line-of-sight wind amplitude variations (or wind latitudinal gradients) on the order of 5-10 m/s (Widemann et al., 2007), which cannot be achieved by single line fitting.

➢It becomes necessary to measure relative Doppler shifts between two sets of absorption lines (Connes, 1985), while simultaneously monitoring the change in spectral calibration with time (Widemann et al., 2008, Machado et al. 2014).

➢The measured Doppler shifts using CFHT/ESPaDOnS have individual formal accuracies of 5-10 m s^{-1}, and their signs and magnitudes are generally consistent with zonal winds inferred from cloud tracking.

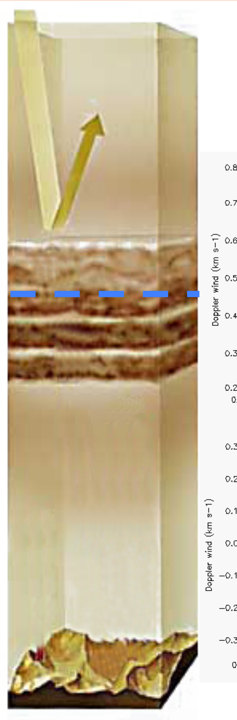
Doppler shifts measurements along the null Zonal wind meridian

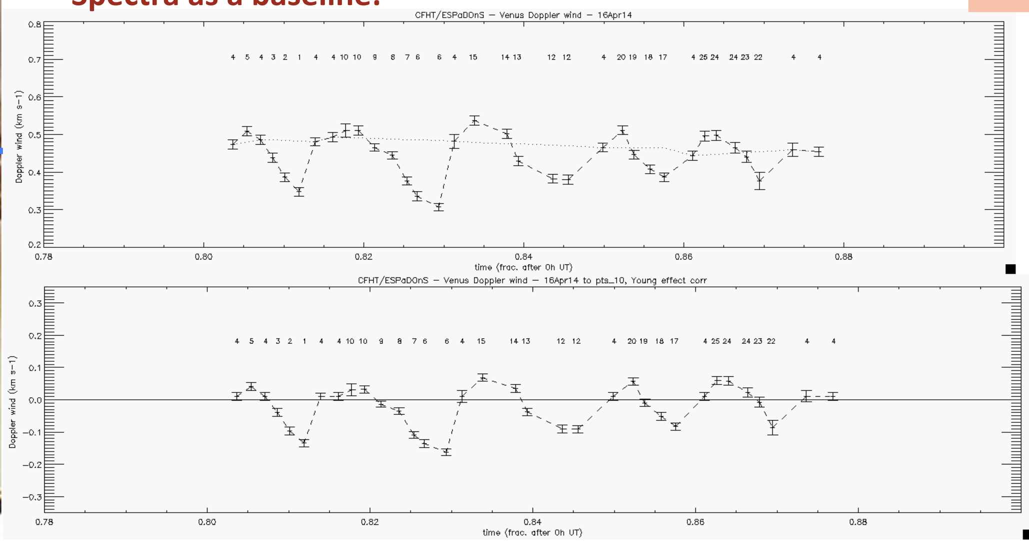




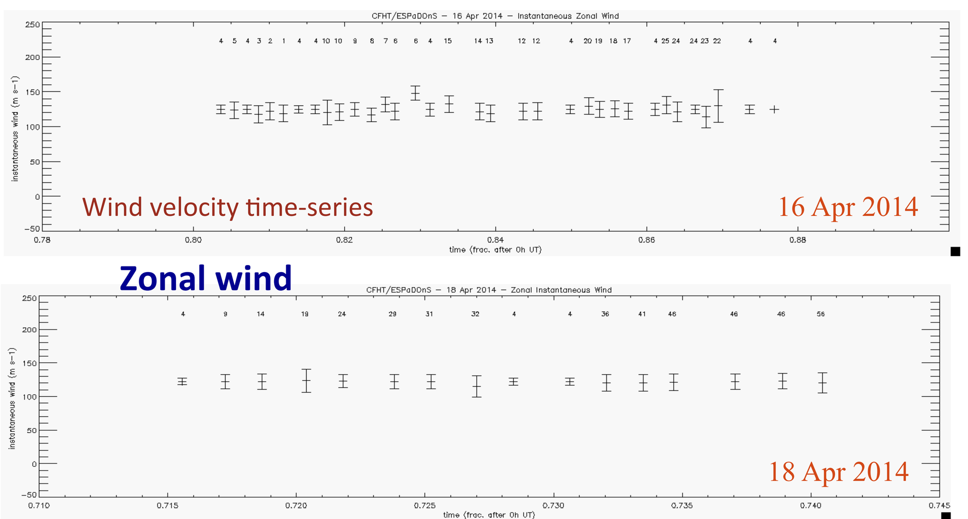
1 - Doppler shifts and retrieval of related velocities:

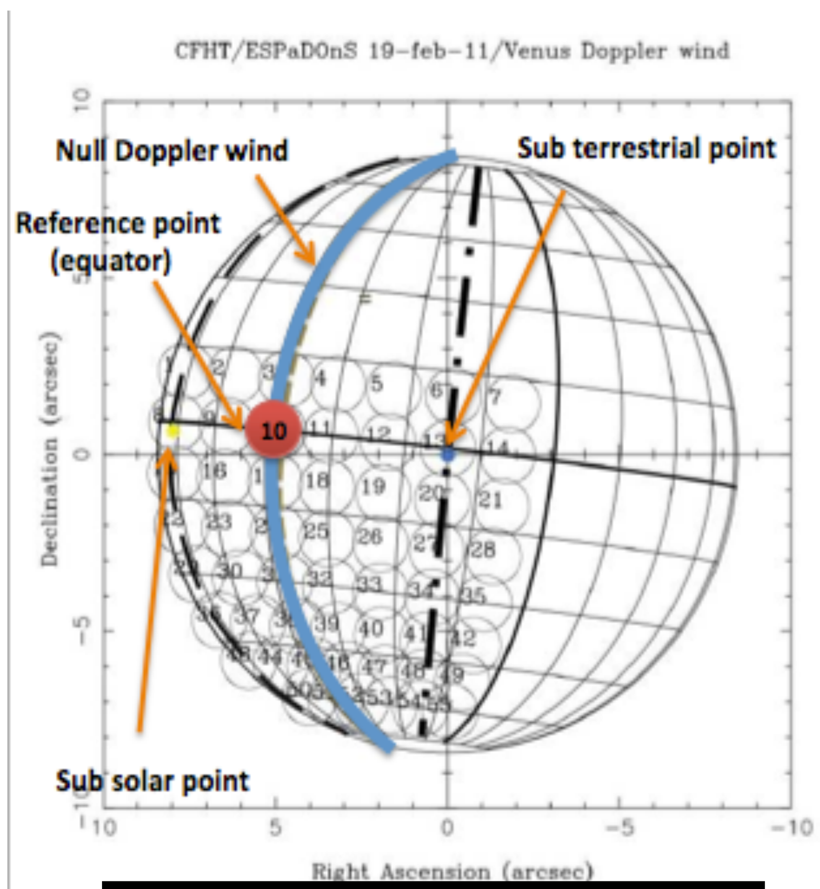
2 - Calibration of the Doppler velocities using the reference Spectra as a baseline:



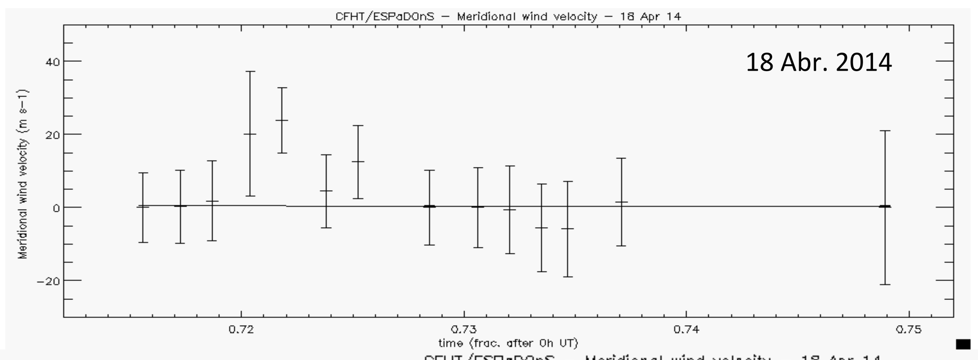


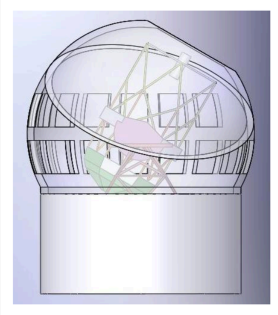
Instantaneous cloud top wind, zonal, 16 and 18 April 2014

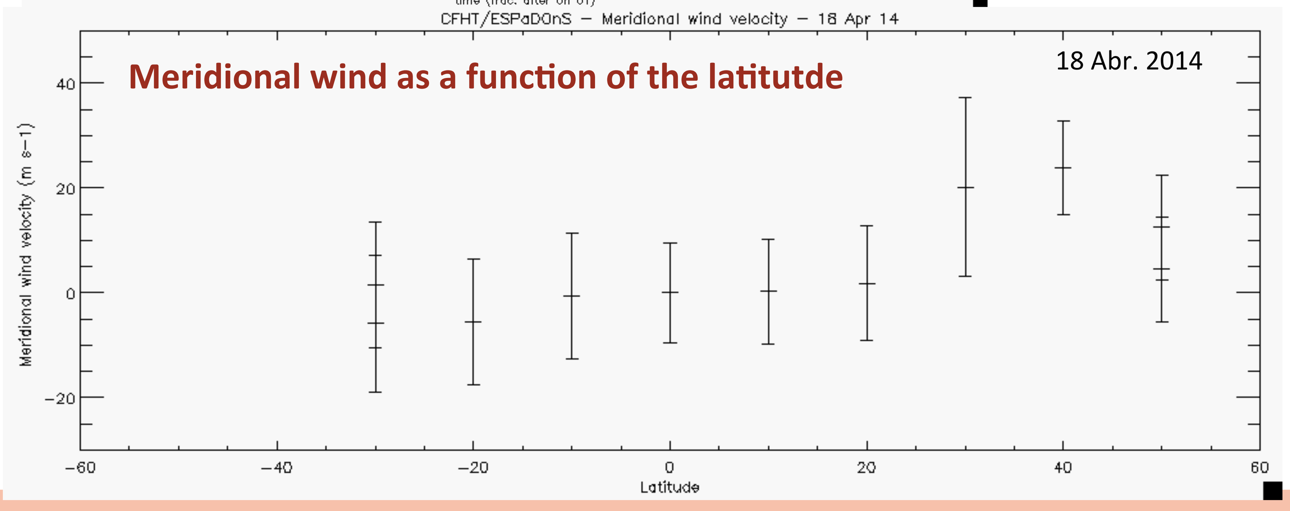




Meridional wind time series



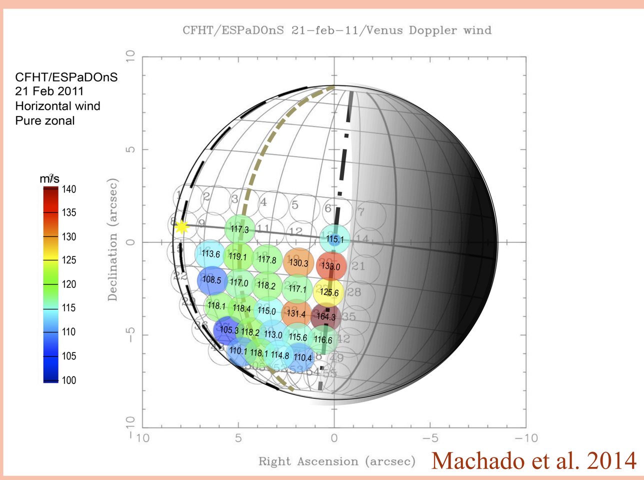




Comparison Ground based Doppler velocimetry and cloud tracking Galileo and VIRTIS UV results

Previous measurements by Pioneer Venus, reanalyzed in Limaye et al. (2007), showed the presence of high latitude zonal jets close to 50 degrees latitude in both hemispheres, with a slight asymmetry between the northern and southern ones.

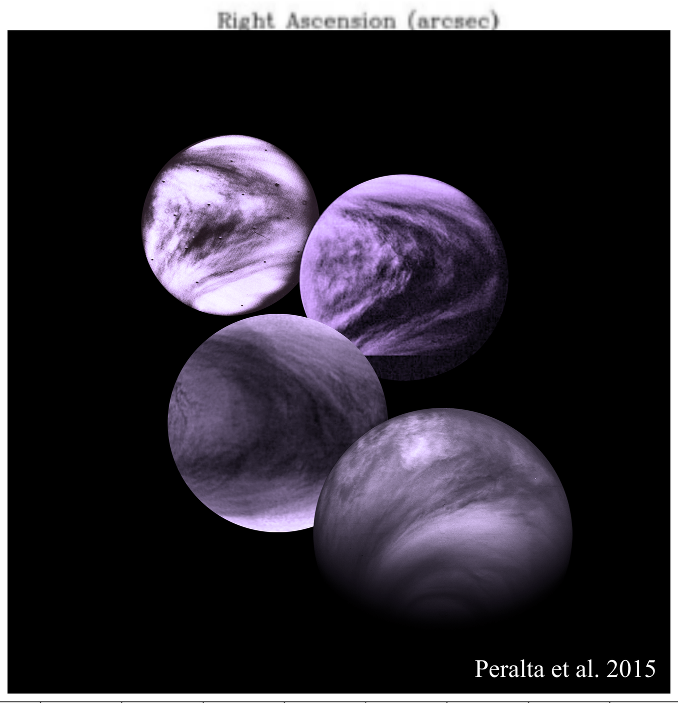
•However, long temporal averages of cloud-tracked winds by the Galileo SSI (Peralta et al., 2007), and by Venus Express VMC and VIRTIS (Sánchez-Lavega et al., 2008; Moissl et al., 2009) do not display clear evidence for high latitude jets at cloud tops, although shorter time scale averages of VMC measurements in Moissl et al. (2009) indicate that jets may occur but are short lived.

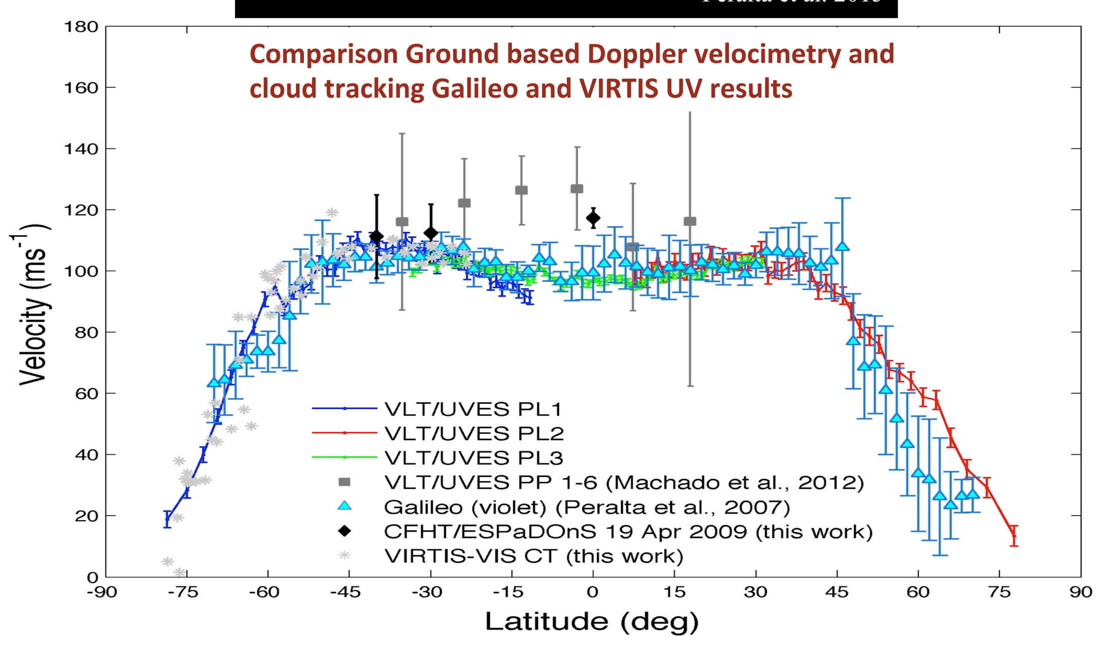


Machado et al. 2014

•Rather than being discrepant, different wind measurements provide important insight into the variability of the circulation.
•We measure instantaneous zonal winds providing additional evidence for the occasional presence of jets, waves and, in general, for variability. The realization that latitudinal wind profile with jets such as measured by Pioneer Venus is likely to be barotropically unstable (Limaye et al. 2009), is an argument in favor of vatiability.

•Our ESPaDOnS present work observations of small scale perturbations (and in previous work of Machado et al. 2014 and with VLT/UVES (Machado et al., 2012)) points to small scale wave motions as the likely processes by which the instability unfolds.


Peralta et al. 2015



VIRTIS-M cloud top tracking
V_{eq} = - (102 ± 10) m/s
(Sánchez-Lavega et al., 2008)
V_{eq} = - (112 ± 5.8) m/s
(Machado et al. 2014)

Ground-based Doppler - sequential
2-4 Jul. 2007 :
V_{eq} = - (104 ± 10) m/s
(Widemann et al., 2008)
19-21 Feb. 2011
V_{eq} = - (117 ± 14) m/s
(Machado et al. 2014)

Ground-based Doppler – long slit
May 2007 :
V_{eq} = -(106 ± 21) m/s
to -(127 ± 14) m/s
(Machado et al., 2012)

Coherence between ground-based and VEx cloud tracking for the background, longitudinally averaged, zonal circulation

Conclusions and Prospects

➢ The data taken at CFHT/ESPaDOnS on 16-21 April 2014, in coordination with Vex measurements, allows monitoring the wind variability at cloud tops.

➢For Doppler velocimetry at visible wavelengths the optical depth reaches unity at 70 km (Ignatiev, 2009), which is also the altitude studied with cloud tracking in the UV, with both VEx/VIRTIS and VEx/VMC (Sánchez-Lavega et al., 2008; Moissl et al., 2009). This allows a direct comparison of magnitudes and spatial variations obtained with VLT/UVES and with Pioneer Venus, Galileo (SSI), and Venus Express.

➢ Our Doppler retrievals are in general good agreement with previous measurements based on cloud tracking (Del Genio and Rossow, 1990; Limaye et al., 2007; Peralta et al., 2007; Sánchez-Lavega et al., 2008; Moissl et al., 2009). However, we can already claim that the averaged zonal wind measured is 10-20 m/s higher then previous results, see: *Kouyama et al., 2013; Khatuntsev et al., 2013.*

➢ We retrieve the same order of magnitude and latitudinal variation of Pioneer Venus, Galileo and VEx/VIRTIS measurements, which cross-validates both techniques and provides reasonable confirmation that cloud tracking and Doppler methods both retrieve the velocities of air masses to first order.

➢ We detect a meridional wind (ongoing work). The cloud tracked winds based on VMC/Vex and VIRTIS-M are being retrieved at this time.

➢The Doppler velocimetry is currently the only ground-based technique able to derive the instantaneous wind's velocities, allowing cross-comparison with cloud-tracked winds from VEx VIRTIS-M and VMC UV images, and to study short-term variability.

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