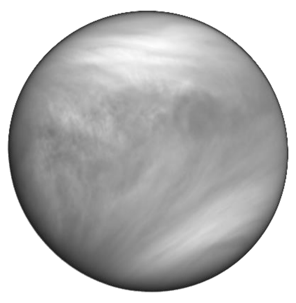

Venus' cloud top wind measures: coordinated Akatsuki/UVI (cloud-tracking) and TNG/HARPS-N (doppler velocimetry) observations

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Abstract

The measure of both zonal and meridional wind velocities at cloud top is essential to our understanding of the dynamics of Venus' superrotational atmosphere. Venus' atmospheric circulation is characterized by a global retrograde zonal wind that peaks at cloud level where the atmosphere spin 60 times faster than the planet's surface. We present new coordinated observations of both zonal and meridional wind amplitude and its variability at Venus cloud-tops (~70 km) based on two complementary techniques: (1) space-based cloud-tracking using JAXA's Akatsuki/UVI imaging, and (2) ground-based Doppler velocimetry using TNG/HARPS-N.

Akatsuki

1 Observations

The JAXA's Akatsuki observations were made between 26 and 31 January 2017, during orbit number 39. The *UltraViolet Imager* (UVI) on board Akatsuki *Venus Climate Orbiter* (VCO) [1] acquired images using the 385 nm filter, covering Venus' dayside local time from 7:30 to 18:00 and latitudes from 70°S to 80°N (fig.1). These images track UV cloud features, originated by a yet unknown UV absorber, at about 68-71 km [2] [3] [4].

2 Method

cloud-tracking

The cloud-tracking technique used is based in a phase correlation method between images developed by Peralta et al. 2007 [6]. Each image pair was processed to enhance the contrast and then geometrically projected into a cylindrical or polar projections, to search for low latitude or high latitude cloud features, respectively. We analyzed a total of 18 images, 3 from each of the 6 days of observation, each separated by ≈ 2 h, granting a total of 4035 cloud tracers from the full observation campaign.

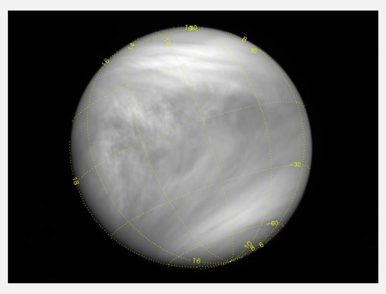

Fig.1 Venus image taken by UVI/Akatsuki 385 nm filter, at 26/01/2017 17:34:47 UT.

3 Results

The results presented in this work (fig.4) show evidence of an asymmetry on zonal wind speed between northern and southern hemisphere - velocities on the southern hemisphere are generally higher, in the order of 5-10m/s – more particularly noticeable on the results of day 26. This N-S asymmetry was also measured by Horinouchi et al. (2018) [11], using Akatsuki UVI. A comparison of zonal wind results from both Akatsuki (dec2015-mar2017 data [11]) and VenusExpress (Vex) (2006-2012 data [13]), is shown in fig. 5.

As for meridional wind (fig.6), our results are consistent with previous cloud-tracking data, both from Akatsuki's and VenusExpress' (VEx) observations ([11], and [13] repectively).

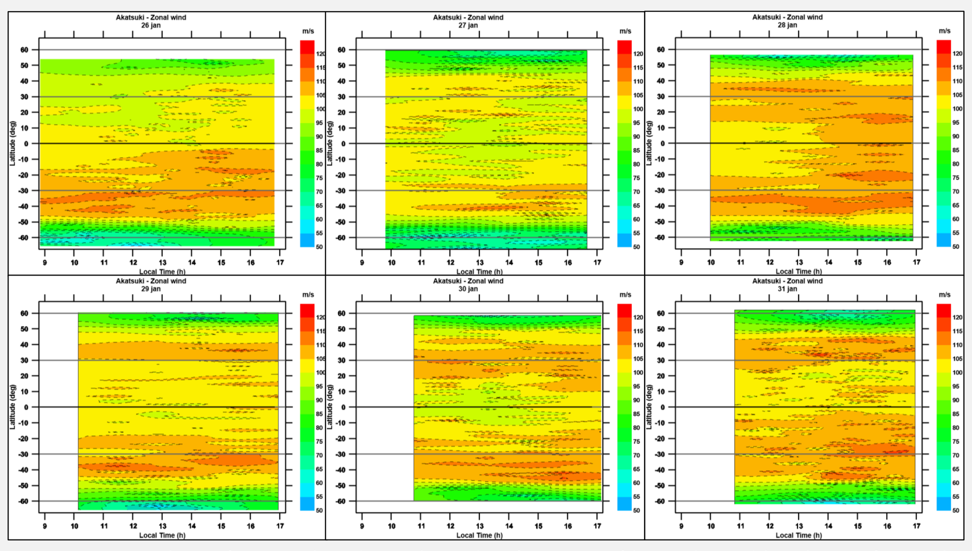

Fig.4 Contour plots of interpolated zonal wind in function of latitude and local time for each day (26-31 January), from Akatsuki/UVI results. Zonal wind velocity represented as a color code.

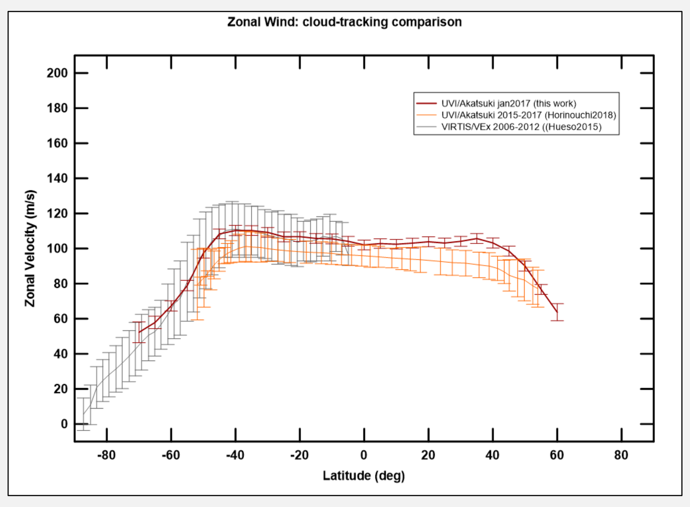

Fig.5 Comparison of zonal wind results from different cloud-tracking space observations. The legend of the figure refers to the instrument/mission, date of observations and respective scientific article.

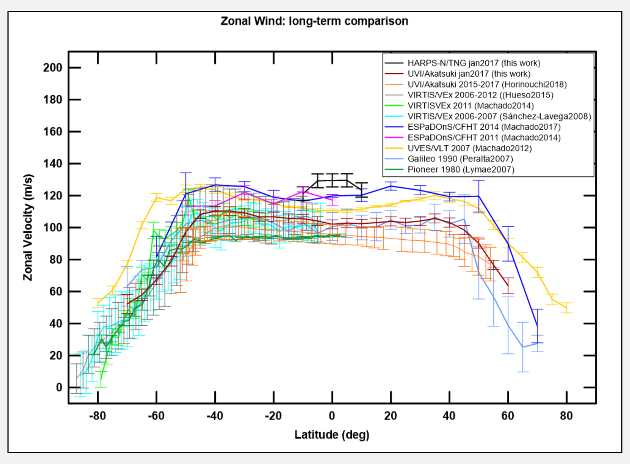

Fig.9 Long-term comparison of zonal wind at Venus' cloud-top from both ground and space observations. The legend of the figure refers the instrument/mission-telescope, date of observations and respective scientific article.

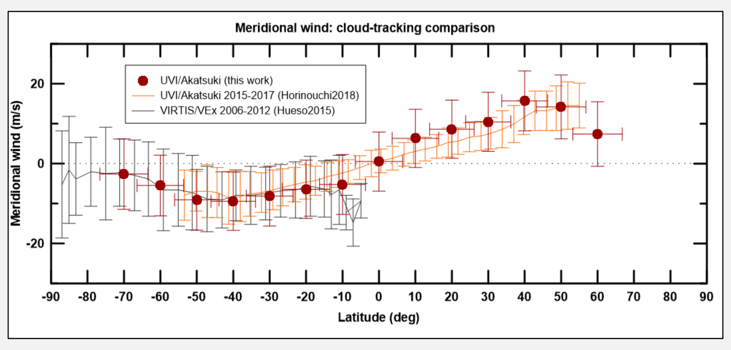

Fig.6 Akatsuki/UVI meridional winds: weighted average of latitude bands (10° binning) from the results of all six days of observation. Comparison with previous cloud-tracking space observations: VIRTIS/VenusExpress from (Sánchez-Lavega et al. 2008) and UVI/Akatsuki (Horinouchi et al. 2018)

HARPS-N

The ground observations took place in January 28th to 29th 2017. HARPS-N (High-Accuracy Radial-velocity Planetary Searcher - North), installed at *Telescopio Nazionale Galileo* (TNG) is a fiber-fed echelle spectrograph which has a field of view (FOV) of 1", a wavelength range of 383-693 nm and a spectral resolution of R=115000 [5]. This was the first time HARPS-N was used to study the atmosphere of a Solar system body. A diagram of the ground observations is presented in fig.2.

doppler velocimetry

The Doppler shift measured in solar light scattered on Venus dayside is the result of two instantaneous motions: (1) a motion between the Sun and Venus upper clouds particles, which scatter incoming radiation in all directions including the observer's; (2) a motion between the observer and Venus clouds (topocentric velocity of Venus cloud particles in the observer's frame). The measured Doppler shift is the combined effect of these instantaneous motions (see fig.3). At half-phase angle (HPA) the relative zonal velocities of particles toward the source of incoming radiation and towards the observer cancel each other out. Thus, a non-zonal wind regime, such as meridional wind flow, should explain the Doppler shifts observed along the HPA meridian.

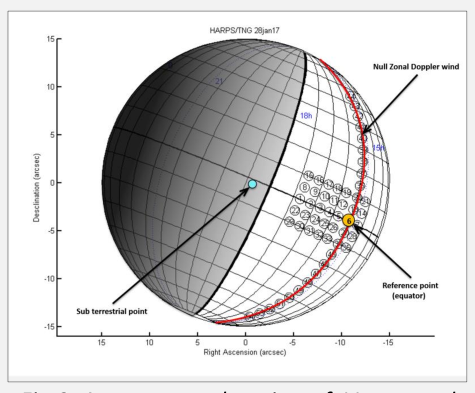

Fig.2 Aspect, angular size of Venus and pointing geometry as seen from Earth on January 28. RA and DEC axis are in arcsec in relation to the center of Venus. Solid black circles represents HARPS-N FOV as seen in Venus disk, in each position observed. Red solid line is in the half-phase angle (HPA) meridian.

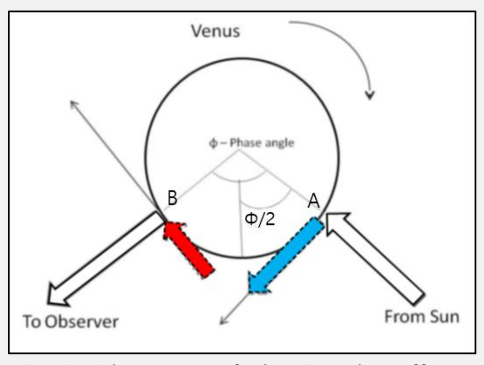

Fig.3 Schematics of the Doppler effect, considering a single scattering approximation. The direction of the Venus' rotations is shown by the top arrow. The solid white arrows represent radiation being absorbed (right hand side) and emitted (left hand side) without Doppler effect. Dashed arrows represent radiation being absorbed (red) or emitted (blue) with the respective Doppler effect.

The Doppler velocimetry method used in this work is based on the technique used by Machado et al. (2017) [7] (which was developed by Widemann [6] and Machado [9] [10]. Using the depth of CO_2 bands in VEx/VIRTIS-M combined with VEx/VMC UV images, Ignatiev (2009) [3] stated that the optical depth of the cloud haze is nearly 0.6 at 40 mbar, and varies as $\lambda^{-1.7}$, implying that a $\tau = 1$ level is reached within one scale height of the clouds top roughly at 70 km of altitude.

The zonal wind results both from UVI/Akatsuki and HARPS_N/TNG show evidence of a thermal tide near the evening terminator (fig.4 and fig.8), where zonal wind velocities are higher in the order of 10 m/s. This existence of this thermal tide has been mentioned in previous studies ([7] [10] [12] [13]).

The meridional winds obtained with HARPS-N (fig.7) are consistent with previous doppler results and present evidence of an Hadley-type cell extending to latitudes near the cold collar structure, up to 60° latitude.

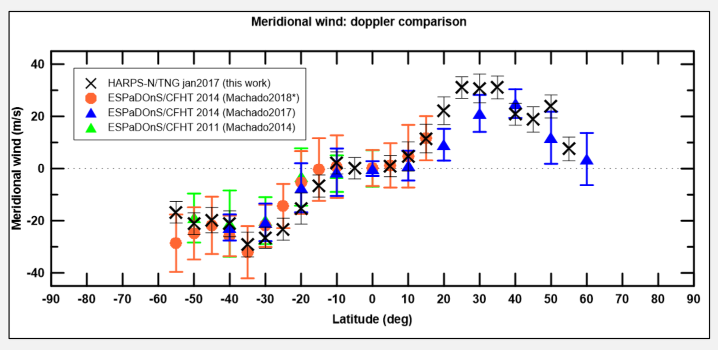

Fig.7 Comparison of meridional wind results retrieved from different observations and telescopes/instruments, using the doppler velocimetry technique. The legend of the figure refers to the instrument used, date of observations and respective scientific article

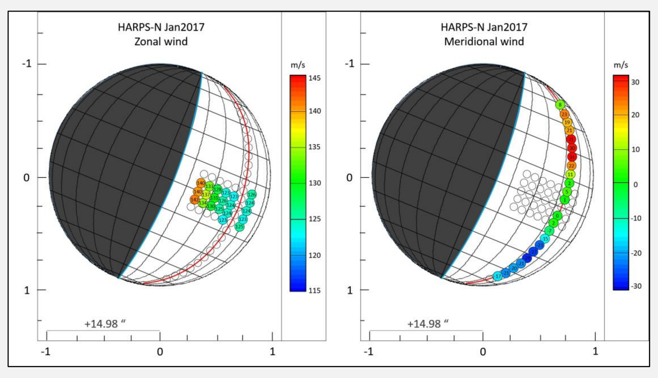

Fig.8 Zonal (left panel) and meridional (right panel) wind (rounded to unit using a color code) retrieved by HARPS-N. Solid circles represents each pointing of the instrument FOV (as in fig.2). The red solid line is the HPA meridian. Right ascension and declination are relative to the centre of Venus' disk. The meridional wind follows a equator to pole direction, with positive/negative magnitude for the northern/southern hemisphere respectively.

4 Conclusions

- ✓ The retrieval of Venus' zonal and meridional wind from different observations (space and ground based), and different techniques (cloud-tracking and doppler velocimetry), is essential to (1) cross-validate different observations and techniques; (2) retrieve complimentary results (different geometry of observations, instantaneous/averaged velocities); (3) constrain cloud-top dynamics and superrotational mechanisms.
- ✓ We present (fig.7) the most precise meridional wind latitudinal profile ever retrieved, including space observations. This result emphasize the uniqueness and importance of the ground-based doppler velocimetry technique in the constrain of Venus cloud-top wind circulation.
- ✓ The zonal winds retrieved from doppler velocimetry present magnitudes higher than winds retrieved by cloud-tracking, in the order of 10-15 m/s (noticeable in fig.9). Meridional winds also present a difference of about 10 m/s (higher for doppler winds) at the peak of its magnitude, at around 40° N and S (fig.6 and fig.7).
- ✓ HARPS-N zonal wind results show higher velocities at central latitudes, between 10°N and 10° S when compared with the results obtained by Machado et al. ([7] [9] [10]), where central latitudes near the equator present homogeneous lower velocities (see fig.9).

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