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Dynamics of the Venus atmosphere from a Fourier-transform analysis

O. Lanciano[1], G. Piccioni[1], R. Hueso[2], A. Sánchez-Lavega[2], and J. Peralta[3]

[1] IASF-INAF Roma, Via Fosso del Cavaliere, 100, Roma, Italy.
e-mail: `orietta.lanciano@iasf-roma.inaf.it/orietta.lanciano@gmail.com`
[2] Universidad del Pas Vasco, Alda, Urquijo s/n, 48013, Bilbao, Spain.
[3] Observatorio Astronomico de Lisboa, Tapada da Ajuda / 1349 - 018 Lisboa, Portugal.

Abstract. The radiance escaping from the Venus deep atmosphere into space at 1.74 μm, one of the atmospheric window, is modulated by the opacity of the lower clouds at about 47 km and it can be effectively used to probe the layer at this altitude. We have used the VIRTIS (Visible and InfraRed Thermal Imaging Spectrometer) instrument onboard the Venus-Express spacecraft able to obtain images of the South hemisphere with a typical projected field of view covering 40° in latitude and 50° in longitude when observed from the apocenter, at a distance of about 65000 km. From this radiance it is possible to characterize different dynamical regimes present in the lower cloud. The observed cloud features have very different morphologies, from bland regions with a few structures to chaotic regions highly contrasted. VIRTIS observations are effectively used to map the dynamical recurrent patterns in the lower clouds layer and these are investigated through a Fast Fourier Transform analysis. The method uses a numeric set of indicators, defined starting by the FFT power spectrum, to differentiate automatically the cloud regions with laminar and turbulent dynamical regimes. The difference between the spectral slopes of the FFT at low frequency is identified as an indicator to detect automatically a laminar or turbulent behavior regime. Another identified parameter related to the cloud turbulent-laminar aspect is the difference between the power spectrum of the first wavenumber and the mean value of the higher power spectrum wavenumbers. This is able to highlight the different dynamical conditions in case of turbulence at the lower scale and thus it removes the ambiguity present in the range of distribution of the spectral slopes when transverse laminar flows respect to the zonal motion or gravity wave on laminar flow are present.

Key words. Planets and planetary systems: dynamics – Planets and planetary systems: atmospheres – Instruments, observational techniques, and data processing: FFT analysis.

1. Introduction

The aim of this work is to show a method for a self consistent quantitative evaluation of the dynamical recurrent patterns characterizing the lower cloud layer of Venus nightside. This clouds layer is effectively probed by using the thermal emission detectable at 1.74 μm in the nadir images acquired by the hyperspectral imager VIRTIS onboard the Venus-Express spacecraft (Drossart et al.

Send offprint requests to: O. Lanciano

2007) (Piccioni et al. 2007). It is also possible to study the variability of the dynamical regions by using images acquired at different times (Sánchez-Lavega et al. 2008). The instrument provides images with a typical projected field of view covering 40° in latitude and 50° in longitude when observed from the apocenter, at a distance of about 65000 km (Piccioni et al. 2007). The images at 1.74 μm allow to sense the cloud layer at an altitude of about 47 km over the surface (Carlson et al. 1991). This cloud layer presents a mixture of cloud textures in the range from bland regions with a few structures to chaotic regions highly contrasted (Peralta et al. 2008).

The Fast Fourier Transform of the image is calculated along a line parallel to the zonal direction and then the FFT power spectrum (FFTPw) is used to retrieve specific parameters able to differentiate quantitatively the latitude regions corresponding to different dynamical regimes like: turbulent, laminar, transverse laminar flux respect to the zonal direction. In addition, the presence of gravity waves in laminar regimes is effectively detected by this technique.

2. Methodology

The image at 1.74 μm is first selected from the hyperspectral cube, then its calibrated radiance is mapped into a latitude-longitude cylindrical grid by means of a linear interpolation on a regular grid of points, with steps of 0.1 degrees (Peralta et al. 2007). The mapped radiance is then selected along a scan at a fixed latitude with longitudinal extension of 1000 km. The FFT is finally calculated at each available latitude and the relative FFTPw is retrieved (ex. in Fig. 1).

The fixed sample extension along the zonal direction ensures that we can actually compare results from different latitudes and different images. In this case the explored wavenumber range is the same for all the samples. Once that the FFT is computed, the FFTPw is fitted by a bilinear function in two different ranges of wavenumbers, giving two slopes: 1) slope1: 1000 $\div$ 200 km (medium scale); 2) slope2: 200 $\div$ 40 km (local scale). We have selected these ranges, after a certain number of attempts, to obtain the information more meaningful possible by the signal: it is interesting to notate that they turns out to be in good agreement with the ranges suggested by Nastrom et al. (1984). The selection for medium and local scales highlight more properly specific differences present in the image texture related to specific dynamical conditions. This general behavior of the power spectrum slopes provides the indicators for our study. This is because the FFTPw slope is related to the energy transfer in the atmosphere between different scales of motion, as explained by the classical turbulence theory for the kinetic energy spectra (Kolmogorov 1941).

The insensitivity of the FFT analysis from the different field of view constrained by the observation in orbit is an important point for this study. It ensures that is possible to compare the parameters coming from the FFT for images in sequence zooming the same cloud region during the spacecraft motion. The information on the slopes may be then synthesized in a single parameter **Diff**, defined as $Diff = (slope2 - slope1)$.

The parameter Diff alone is however not sufficient to infer an unambiguous response in case of transverse laminar flows or gravity waves in laminar flow. In such as cases, the parameter Diff gives comparable values as for turbulent flows. An additional parameter, **Gap**, removes this ambiguity. Gap is defined as the difference between the FFTPw value of the 1° wavenumber (for 1000 km) and the FFTPw mean value in the range 40 $\div$ 20 km, as shown in Fig. 1. In some sense, it is a way to evaluate quantitatively the roughness of the image: the smoother the image texture, the smaller the Gap is.

Finally the whole set of (Diff;Gap;latitude) data is plotted in the Diff-Gap plot (latitude in color scale). Analyzing visually the cases with different dynamical regime we have found empirically how to associate them with specific coordinate in the Diff-Gap plot.

3. Results

This method has been tested on about one hundred images with different cloud dynamical

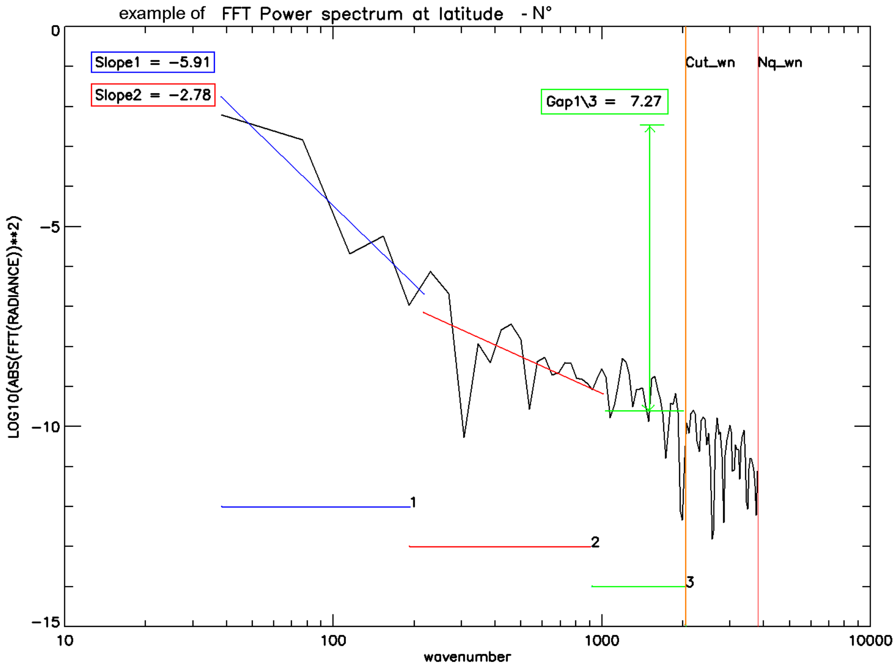


Fig. 1. FFTPw of selected samples with fixed extension of 1000 km. This choice determines a unique wavenumber range for the FFT analysis. In the same color the wavenumber range of FFTPw linear fit and its correspondent slope value. The Gap is obtained as the distance from the FFTPw of the 1° wavenumber and the FFTPw mean value of the higher wavenumber range.

textures. In the following sections are showed the results for only four ”pure” cases (images of these in Fig.2 a1 and b1, Fig.3 c1 and d1), with a relatively easy association to specific dynamical conditions:

a. **Laminar**;
b. **Laminar / turbulence**;
c. **Transverse* laminar / turbulence** (*respect the zonal direction);
d. **Laminar with gravity waves / turbulence**.

The results are plotted for the slopes vs latitude (Fig.2 a2 and b2, Fig.3 c2 and d2), Gap vs latitude and Diff vs latitude (Fig.2 a3 and b3, Fig.3 c3 and d3), and finally the Gap vs Diff vs latitude (Fig.2 a4 and b4, Fig.3 c4 and d4). The last kind of plots, Gap vs Diff vs latitude, resumes the main information of the previous plots and highlights the existence of critic values for Diff (Diff = 4) and Gap (Gap = 7.5) for which there is a change of the cloud dynamical regimes. In this way, it is possible to associate a direct correspondence between the four quadrants defined by the critic values and the dynamical conditions:

1° quadrant (Diff > 4.0 and Gap > 7.5) is associated to **gravity waves on laminar fluxes**;

2° quadrant (Diff < 4.0 and Gap > 7.5) is associated to **turbulent fluxes**;

3° quadrant (Diff < 4.0 and Gap < 7.5) is associated to **transverse laminar fluxes**;

4° quadrant (Diff > 4.0 and Gap < 7.5) is associated to **laminar fluxes**.

Fig. 4 resumes graphically these results and provides a quantitative reference to compare future FFT image analysis data.

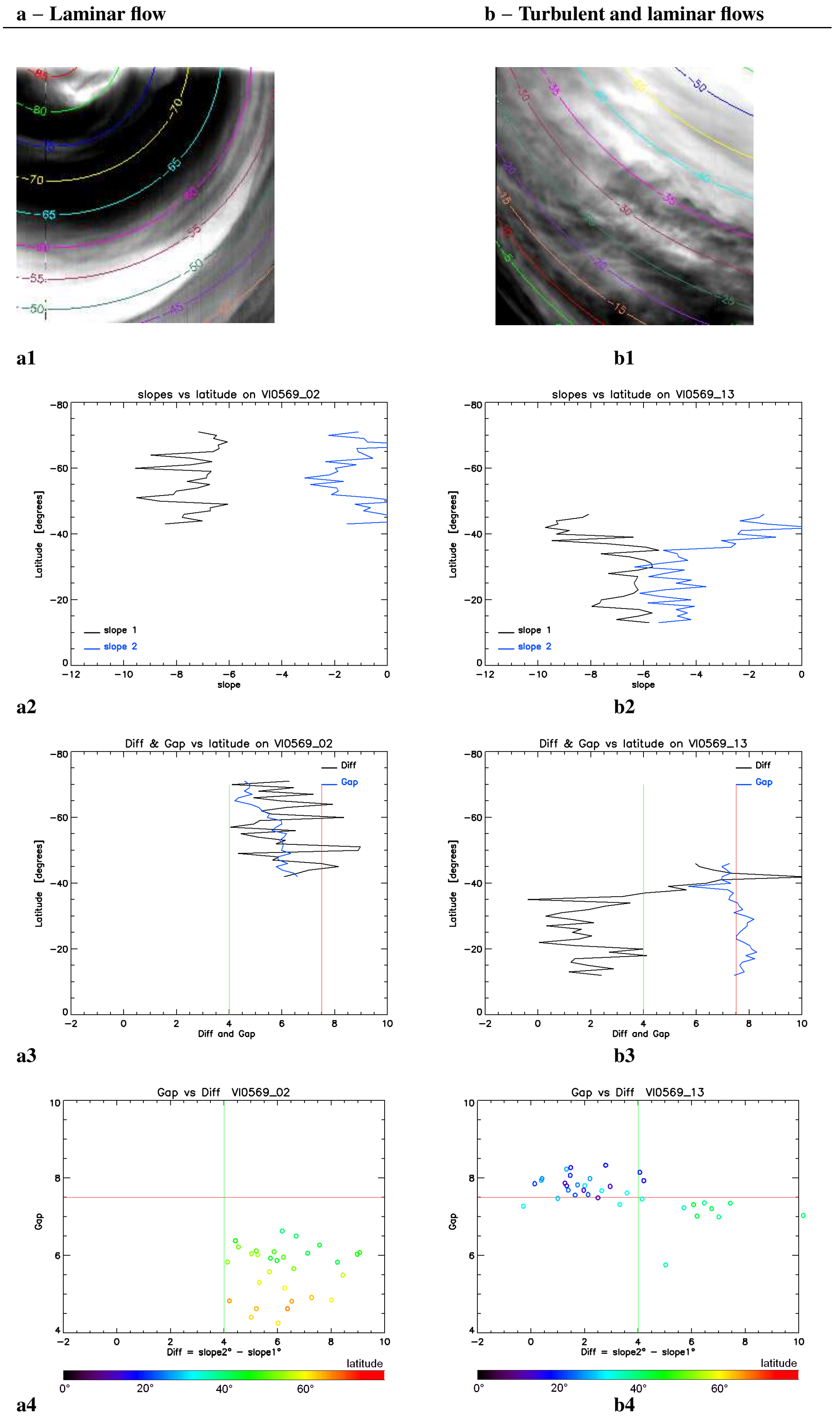
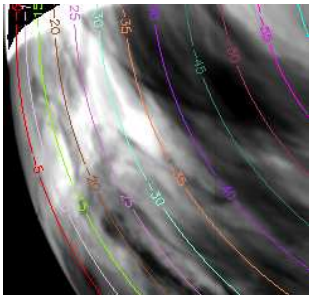


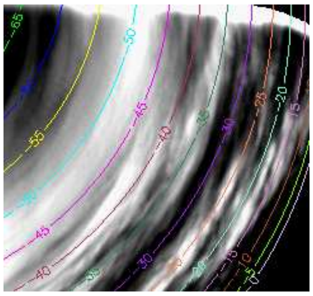
Fig. 2. Column **a** – case of **Laminar flow**: in **a1** the image at 1.74 μm; in **a2** the plot of FFTPw slopes vs latitude; in **a3** the Gap vs latitude plot and the Diff vs latitude plot; in **a4** the Diff and Gap plot vs latitude (in color). The same of column **a** in the column **b** in case of **Turbulent and laminar flows**.

c – Turbulent and transverse laminar flows

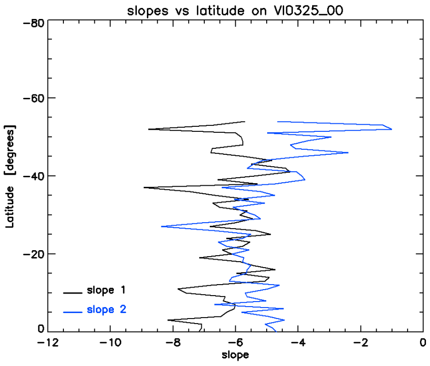
d – Turbulent flow and laminar flow with gravity waves



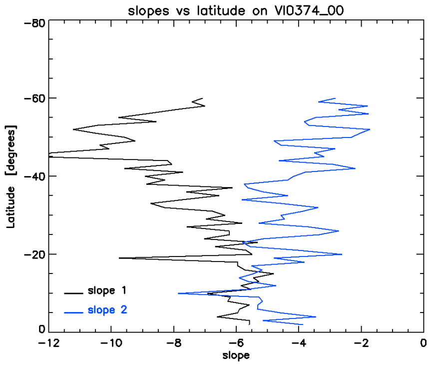
c1



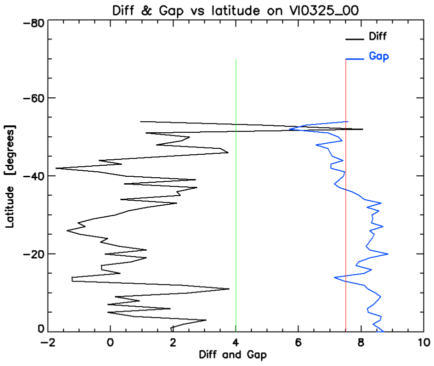
d1



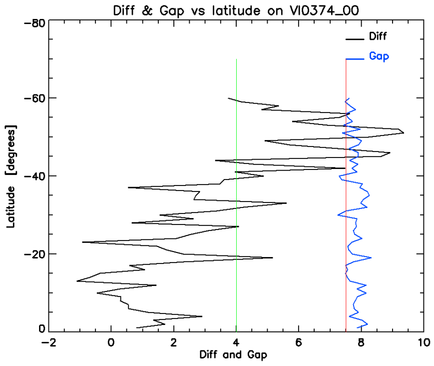
c2



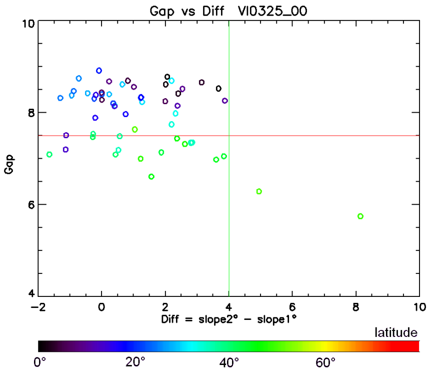
d2



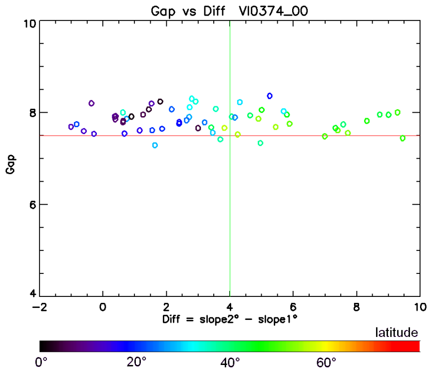
c3



d3



c4



d4

Fig. 3. Column **c** – case of **Turbulent and transverse laminar flows**: in **c1** the image at 1.74 μm; in **c2** the plot of FFTPw slopes vs latitude; in **c3** the Gap vs latitude plot and the Diff vs latitude plot; in **c4** the Diff and Gap plot vs latitude (in color). The same of column **c** in the column **d** in case of **Turbulent flow and laminar flow with gravity waves**.

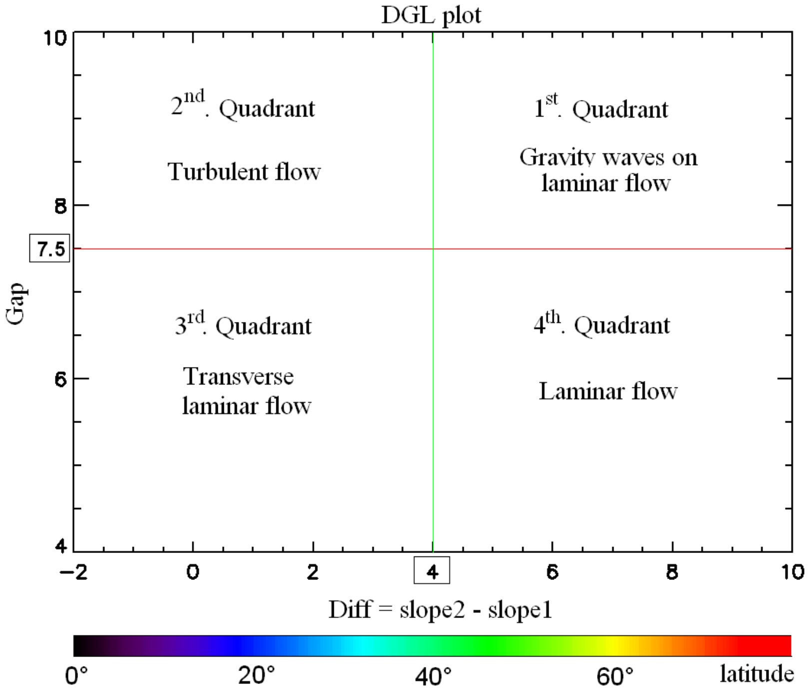


Fig. 4. Each point on the Diff-Gap graph is obtained from the FFT image sampled at fixed latitude. The origin of the graph is found empirically and it is (Diff=4;Gap=7.5). The position in the quadrant is linked to a particular dynamical condition as determined by the comparison with almost "pure" cases. For gravity waves on laminar flow the point (Diff;Gap) is in the 1° quadrant. In case of transverse laminar flux the point is in the 3° quadrant. The points for turbulent fluxes, generally presents at middle latitudes, are always positioned in the 2° quadrant and the laminar fluxes, characteristic of the regions close to the polar vortex and with the lower wind speed values, are in the 4° quadrant.

4. Conclusions

We have presented here a method that, starting from the Venus lower clouds images by VIRTIS, is able to detect in a self consistent way the dynamical conditions linked to specific cloud textures. This is obtained starting from appropriate parameters retrieved by the FFT image analysis, specially through the parameters named Diff and Gap. These two parameters provide complementary information to describe the dynamical state of the lower clouds layer. The position on the graph Diff-Gap of the data set (Diff;Gap;latitude) is an effective way to detect particular dynamical regimes. This method was developed to be applied at Venus but it can be applied in principle to other planets.

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