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# Instantaneous three-dimensional thermal structure of the South Polar Vortex of Venus

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ABSTRACT

The Venus thermal radiation spectrum exhibits the signature of $CO_2$ absorption bands. By means of inversion techniques, those bands enable the retrieval of atmospheric temperature profiles. We have analyzed VIRTIS-M-IR night-side data obtaining high-resolution thermal maps of the Venus south polar region between 55 and 85 km altitudes. This analysis is specific to three Venus Express orbits where the vortex presents different dynamical configurations. The cold collar is clearly distinguishable centered at ~62 km (~100 mbar) altitude level. On average, the cold collar is more than 15 K colder than the pole, but its specific temperature varies with time. In the three orbits under investigation the South Polar Vortex appears as a vertically extended hot region close to the pole and squeezed by the cold collar between altitudes 55 and 67 km but spreading equatorwards at about 74 km. Both the instantaneous temperature maps and their zonal averages show that the top altitude limit of the thermal signature from the vortex is at ~80 km altitude, at least on the night-side of the planet. The upper part of the atmosphere (67–85 km) is more homogeneous and has long-scale horizontal temperature differences of about 25 K over horizontal distances of ~2000 km. The lower part (55–67 km) shows more fine-scale structure, creating the vortex morphology, with thermal differences of up to about 50 K over the same altitude range and ~500 km horizontal distances. This lower part of the atmosphere is highly affected by the upper cloud deck, leading to stronger local temperature variations and larger uncertainties in the retrieval. From the temperature maps, we also study the vertical stability of different atmospheric layers for the three vortex configurations. The static stability is always positive ($S_T > 0$) in the considered altitude range (55–85 km) and in the whole polar vortex. The cold collar is the most vertically stable structure at polar latitudes, while the vortex and sub-polar latitudes show lower stability values. Furthermore, the hot filaments present within the vortex exhibit lower stability values than their surroundings. The layer between 62 and 67 km resulted to be the most stable. These results are in good agreement with conclusions from previous radio occultation analyses.



## 1. Introduction

About three decades ago, Mariner 10 ultraviolet images revealed a spiral cloud pattern centered at the south pole of Venus, forming a circumpolar vortex (Suomi and Limaye, 1978). Soon after, the Pioneer Venus infrared data showed a "double-eye" thermal structure at the north pole (Taylor et al., 1980; Schofield and Diner, 1983). More recently, the European Venus Express (VEX) mission (Svedhem et al., 2007) confirmed the presence of a similar thermal structure in the south polar region of the planet (Piccioni et al., 2007). On a highly elliptical orbit, VEX monitors the southern hemisphere every 24 h from apocenter at about 66,000 km above the planet's surface. Both the *Visible and InfraRed Thermal Imaging Spectrometer* (VIRTIS, Drossart et al., 2007) and the *Venus Monitoring Camera* (VMC, Markiewicz et al., 2007) have observed the South Polar Vortex since Venus Orbit Insertion in 2006, showing that it is a permanent feature in the venusian atmosphere (Piccioni et al., 2007; Luz et al., 2011; Titov et al., 2012; Garate-Lopez et al., 2013).

VMC imagery is obtained in day-light and has a limited visibility of the polar area due to the low solar illumination. A better view of the vortex is obtained with VIRTIS night-side infrared images (1–5 μm). These images show that the vortex is confined to latitudes higher than 75°S (Piccioni et al., 2007) and that it is highly variable in its morphology, evolving through different configurations (dipolar, elongated oval or nearly circular) but being most

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of the time a transition feature between these configurations (Garate-Lopez et al., 2013). In some cases the vortex preserves an identifiable shape for a few days, but in general it changes its appearance on timescales of 1–2 days (Luz et al., 2011). In addition to variations in shape, the vortex changes much of its characteristic motions. Recent work (Garate-Lopez et al., 2013) has reported that about half of the time the vortex shows a closed circulation pattern that may be concentric with the clouds' morphological center (as expected) but may also be displaced from it. The other half of the time, convergence or divergence circulation patterns, seemingly associated with vertical velocities of up to 0.16 m/s, appear in the vortex. Furthermore, it was found that the vortex is not centered at the south pole but wanders around it in an unpredictable manner. Images of two altitude levels from two observing windows, 1.74 μm sensitive to cloud features at ~42 km above the surface (Barstow et al., 2012), and 3.80 or 5.10 μm, sensitive to the thermal structure and cloud features at ~63 km above the surface (Peralta et al., 2012; Titov et al., 2012; Lee et al., 2012; Haus et al., 2014), indicate that these wandering motions are different at both altitudes, thus showing a vertically curved structure. For the upper altitudes, Luz et al. (2011) found that the vortex's rotation center precesses around the pole with a period of 5–10 Earth days but this precession is only a first approximation to more complex motions (Garate-Lopez et al., 2013).

Our current knowledge of Venus' South Polar Vortex is based mainly on its cloud morphology and motions. In order to interpret its dynamical nature, it is critical to characterize the thermal structure of the vortex, which remains poorly constrained. Piccioni et al. (2007) presented a map of the brightness temperature at 5.05 μm of the southern pole of Venus showing the warm dipolar structure of the vortex (250 K) surrounded by a cold ring (210 K). Thermal maps of the vortex area at different altitudes were obtained by Grassi et al. (2008) from VIRTIS data. These maps showed a smooth distribution of temperature with a maximum difference of about 30 K between the vortex and its surroundings at ~65 km.

Before the VEX arrival, the global thermal structure of the venusian atmosphere was studied by a variety of techniques with data from different space missions. Amongst others, Seiff et al. (1980) studied thermal fluxes measured by the Pioneer Venus descent probes, Roos-Serote et al. (1995) analyzed infrared spectra in the 4.3 μm $CO_2$ absorption band from the Galileo flyby of Venus and Zasova et al. (1999) investigated Venera-15 spectroscopic data in the $CO_2$ band at 15 μm. These measurements were obtained at a variety of epochs, locations over the surface and were sensitive to different atmospheric altitudes.

The Venus Express mission is well equipped to study the thermal structure of the atmosphere. The Venus Radio (VeRa) Science experiment (Häusler et al., 2006) has obtained thermal profiles of the upper atmosphere from 40 to 100 km using radio occultations (Tellmann et al., 2009). The SPectroscopy for Investigation of Characteristics of the Atmosphere of Venus instrument (SPICAV) has gathered thermal data from 80 to 140 km using stellar and solar occultations (Bertaux et al., 2007a, b). These instruments can characterize the vertical temperatures at a single location at a time but cannot provide the thermal field of a large area at a particular time. The VIRTIS instrument is well suited for that task. Night-side thermal emission of the planet in the 3–5 μm range is sensitive to both temperatures and cloud opacities. Grassi et al. (2008) developed a method for obtaining thermal profiles in the venusian night-side mesosphere from radiances measured by VIRTIS-M (the mapping channel of the instrument). This method has been used to produce moderate resolution thermal maps of the polar area from a single orbit (Grassi et al., 2008) and to obtain average temperature fields as a function of latitude, local time, and pressure (Grassi et al., 2010). Additionally, Migliorini et al. (2012) investigated night-side atmospheric temperatures on both hemispheres using VIRTIS-H (the instrument's high-resolution spectral channel) data. Haus et al. (2013) proposed a radiative transfer model and a multi-window procedure to retrieve information about both temperature profiles and cloud parameters of the atmosphere of Venus. This method was subsequently used to produce statistical global maps of temperature and cloud altitudes from VIRTIS-M. The maps show high temperatures and low clouds at both poles consistent with hot vortices with larger thermal variability than the rest of the planet (Haus et al., 2014).

Instead of a statistical study of temperatures in the polar region we aim here to relate the instantaneous dynamics from the wind field to the particular thermal structure of the vortex on different days. In a recent paper, García Muñoz et al. (2013) investigated the radiative transfer problem of thermal radiation from the Venus night-side between 3 and 5 μm with a purpose-built model of Venus' mesosphere. That work explored the impact of the atmospheric temperature, cloud opacity, and the aerosols' size and chemical composition on the emission spectrum and demonstrated the importance of scattering in the upper cloud and haze layers over Venus' mesosphere. In this work we apply the atmospheric model described by García Muñoz et al. (2013) and a variant of the retrieval algorithm detailed in Grassi et al. (2008) to obtain night-side thermal maps of the Venus south polar region between 55 and 85 km altitudes. These maps are discussed in three different dynamical configurations of the vortex whose dynamics in terms of cloud motions has been previously obtained (Garate-Lopez et al., 2013). We also compare the thermal structure with the retrieved motions and study the imprint of the vortex on the thermal field above the cloud level. In Section 2 we describe the selected observations and the thermal retrieval procedure. Thermal and static stability results are presented in Section 3. Finally, we discuss the relation between thermal structure and cloud motions in the vortex in Section 4.

## 2. Observations and thermal retrieval

### 2.1. Selected observations

VIRTIS is an imaging spectrometer that comprises two subsystems (Drossart et al., 2007), a high resolution spectrometer (VIRTIS-H), and a mapping subsystem (VIRTIS-M) which, in turn, combines separate infrared (VIRTIS-M-IR) and visible (VIRTIS-M-Vis) channels. The infrared channel of the mapping subsystem covers the 1.0–5.1 μm range with a spectral sampling of 10 nm and has an instantaneous field of view per pixel of $0.25 \times 0.25$ mrad$^2$. When the spacecraft is observing the south pole from apocenter, the spatial resolution in the $256 \times 256$ pixel image is about 16 km/pixel. The VIRTIS-M-IR data are of particular interest since they allow us to obtain atmospheric temperatures from the same set of images that have been used to retrieve atmospheric winds.

In a previous work (Garate-Lopez et al., 2013), we used VIRTIS-M-IR images to study the polar vortex at 1.74 μm and 3.80 or 5.10 μm over 23 orbits (1 VEX orbit = 24 h). The morphological structure and the associated wind field at two altitudes, ~42 and ~63 km above the surface, were extracted from the images using a supervised correlation algorithm (Hueso et al., 2009). For the current work we have selected three of the best cases in that study, which combine high density of wind measurements, different morphologies of the vortex and high-quality spectral data over the 3–5 μm range in most of the imaged area. These data sets are: orbit 038 (28 May 2006), when the vortex had a dipolar structure with an inverted-S bright filament surrounded by the cold collar, orbit 310 (24 February 2007) with a nearly circular radiant vortex displaced from the south pole by ~7° in latitude, and orbit 475 (08