DAVINCI: Venus Atmospheric Model Comparisons

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The Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission aims to answer long-standing questions regarding Venus' origin using Zephyr, an atmospheric descent probe. Zephyr will be the first probe to take high-resolution aerial photographs of a mountainous tesserae surface as it descends over the Alpha Regio highlands region, which has the oldest surfaces of Venus. The Zephyr's descent trajectory that determines the touchdown in the Alpha Regio, which is crucial for the DAVINCI mission, depends on venus' atmospheric properties and winds. Unfortunately, the atmospheric data for Venus from previous missions is sparse. Therefore, it is essential to consider various atmospheric models and scenarios from past flight data to predict Zephyr's flight performance, specifically landing ellipse. To this end, this work compares three atmospheric models: the Venus Global Reference Atmospheric Model (Venus-GRAM), the Venus Climate Database (VCD), and an empirical wind model developed by Ralph Lorenz for the DAVINCI trajectory simulation and modeling. This paper compares the mean and variations of different atmospheric properties and winds from these atmospheric models. In addition, this work combines the atmospheric properties and the wind variability from the Venus-GRAM with the winds from the Lorenz-based model to have more stressing Venus wind dispersions that allow for more conservative trajectory analysis. Furthermore, this work relies on the DAVINCI landing ellipse size as a metric to measure how robust the trajectory analysis will be to the change in the atmospheric properties and winds of the Venus atmosphere.

I. Introduction

The 2012 Planetary Decadal Survey [1] prioritized studying Venus to answer long-standing questions regarding its origin and processes. These questions involve mysteries such as whether Venus was ever habitable in the past, what is the origin of Venus, why there are extreme atmospheric differences between Venus and Earth despite having similar size and density. In addition, scientists are interested in understanding the atmospheric composition of Venus, understanding how much water Venus had in the past, and understanding how the rock formation and how erosion works on Venus today [2]. Furthermore, understanding the evolution of Venus through time may provide one with more insights into the processes that govern global-scale changes of the planet's environment. To investigate the origins of Venus along with its atmosphere and how they have evolved over the past 4.5 billion years, National Aeronautics and Space Administration (NASA) selected the Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging (DAVINCI) mission to study the planet in the early 2030s.

The DAVINCI consists of two parts: the Carrier-Relay-Imaging Spacecraft (CRIS) and the Probe Flight System (PFS). PFS is the entry vehicle which houses Zephyr, the actual atmospheric probe. CRIS will act as the means of telecommunications between the Zephyr and Earth. CRIS will make two gravity-assist flybys in 2029 and 2030, during which its two onboard instruments will study Venusian clouds and map Venus' ancient highland areas. On the third Venus flyby in 2031, the PFS will separate from the CRIS spacecraft. Within Zephyr, the PFS will be carrying five other science instruments [3]. The primary PFS payload, Zephyr, is about one meter wide, as shown in Figure 1, and is constructed from Titanium. This design allows the Zephyr and its instruments to withstand the crushing atmospheric pressure, sulfuric acid clouds, and scorching temperatures while descending through Venus' atmosphere. From the top of the atmosphere at 145 km, the spacecraft will start its hour-long descent. Approximately 3 minutes into the

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entry, the PFS deploys a parachute designed to withstand the harsh Venusian environment and exposes the Zephyr to the atmosphere for scientific measurements. After 30 minutes of descent on parachute, the Zephyr jettisons from the parachute near 40 km altitude. The atmosphere of Venus near the surface is approximately 90 times denser than Earth's, which allows the Zephyr to decelerate further without requiring the additional drag from the parachute. During the hour of Entry, Descent, and Landing (EDL), the five science instruments onboard Zephyr will collect invaluable data of Venus atmospheric composition and images of Venus surface.

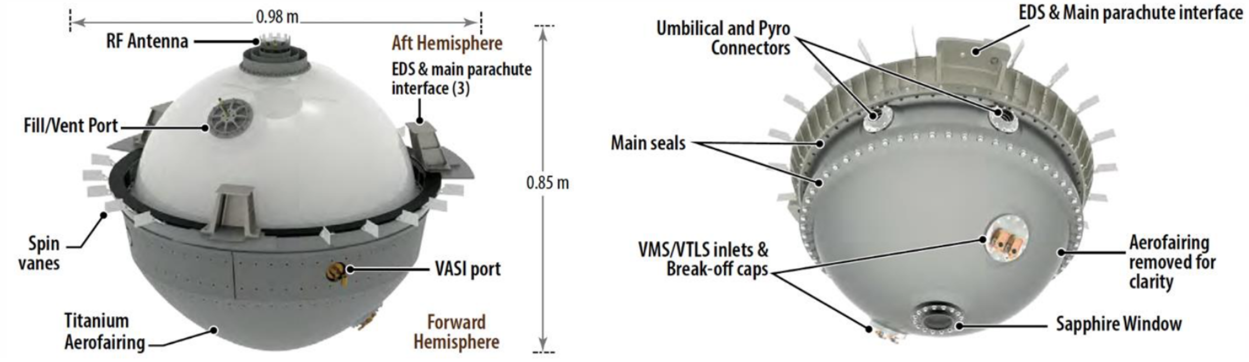


Fig. 1 DAVINCI descent sphere - Zephyr. [4]

Venera 4, which reached Venus in 1967, was the first successful probe to enter the planet's atmosphere. Later missions, such as Venera 5 and 6, were able to transmit some Venus atmospheric data back to Earth. Multi probe Pioneer Venus 2 consisting of five spacecraft entered the atmosphere on 9 December 1978. Out of five spacecraft, one is an orbiter, one is a Large probe and three small probes called North probe, Night probe and Day probe. These four probes carried multiple science instruments and provided invaluable Venus atmospheric data. Soviet VeGa-2 mission was the last probe to descend through venus' atmosphere and land successfully in 1985. This spacecraft landed in the basaltic plains formed by volcanism. However, there are some regions of heavily deformed terrain called "tesserae" found on highland regions of Venus. Scientists believe that the tesserae contains rocks that potentially show signs of form water-rock interactions and continent-building processes. Studying these rocks can confirm this hypothesis that there were hospitable conditions in Venus' past. Zephyr will be the first probe to take high-resolution aerial photographs of a mountainous tesserae surface as it descends over the Alpha Regio highlands region. This region has the oldest surfaces of Venus and allows one to study rocks that are billions of years old. It is, therefore, vital that Zephyr lands in the Alpha Regio area for the success of the DAVINCI mission.

The touchdown of Zephyr in the Alpha Regio, which is crucial for the DAVINCI mission, relies heavily on the EDL sequence used by the PFS, which consists of the entry capsule and Zephyr probe. PFS will reach the entry interface of Venus two days after being released from the CRIS spacecraft. Upon initializing its entry sequence, Zephyr's descent through the Venus atmosphere before touchdown will take approximately one hour. The Zephyr may continue to transmit data after the touchdown if it survives the impact. DAVINCI's entry and descent design is largely inspired by the successful 1978 Pioneer Venus Large Probe, as well as recent advances in EDL modeling and simulation.

EDL trajectory simulations use Venus atmospheric and wind models, which play a vital role in the simulation predictions. Unfortunately, the atmospheric data for Venus collected from several Venera missions and Pioneer probe mission is sparse. To this end, it is imperative to consider various atmospheric models and scenarios from past flight data for predicting Zephyr's flight trajectory. This work compares three atmospheric models considered for DAVINCI trajectory simulation. The first model is the Venus Global Reference Atmospheric Model (Venus-GRAM) [5], which is in turn based on the Venus International Reference Atmosphere (VIRA) [6] derived from Pioneer Venus orbiter and probe data as well as the Venera probe data. The second model considered in this study is the Venus Climate Database (VCD) [7], which is derived from the simulations of the Venus atmosphere with Institut Pierre-Simon Laplace (IPSL) full-physics Venus General Circulation Model (GCM) [8]. The third model is an engineering wind model, referred to as the Lorenz Based Venus wind model from here on, which is based on Pioneer Venus probe data [9].

This paper considers a simulation tool, the Program to Optimize Simulated Trajectories II (POST2) that models the probe's descent trajectory through the Venus atmosphere. As discussed earlier, the probe spends a significant amount of time in the Venus atmosphere, where the winds and other atmospheric properties such as pressure, density and temperature can affect the descent trajectory significantly. Consequently, the touchdown site, which is desired to be over the Alpha Regio highlands region, can be affected based on which atmospheric and wind model to assume. This work studies atmospheric properties' dispersions from two different atmospheric models and wind dispersions from three wind models to analyze their effect on the descent trajectory through the Venus atmosphere. The rest of the paper is organized as follows: Section II discusses the DAVINCI Entry Descent and Landing (EDL) overview. Section III discusses each of the three Venus atmospheric models considered in this work in detail. Section IV presents an Atmospheric comparison considering venus' atmospheric dispersions. Finally, Section V presents the conclusions.

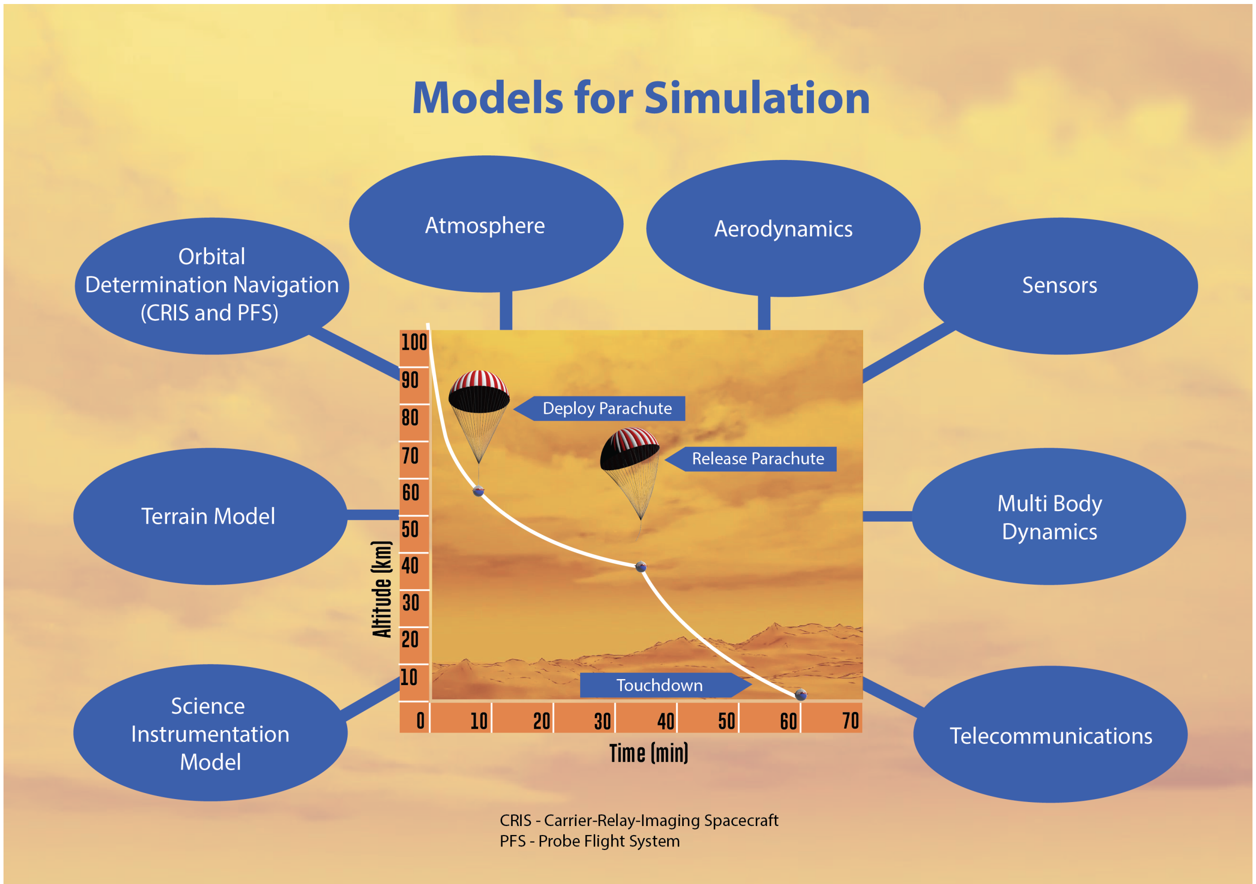


Fig. 2 DAVINCI EDL Simulation Overview.

II. DAVINCI EDL Overview

In 2031, DAVINCI will release its descent probe Zephyr to travel to the surface after exploring the atmosphere of Venus and the Alpha Regio's composition. As discussed in the introduction, the deployment sequence for DAVINCI relies on the flight heritage of the Pioneer Venus probe [4]. The probe decelerates significantly between 100 and 80 km in altitude because of the thick Venus atmosphere. At these altitudes, the probe experiences its maximum deceleration and peak heating. Like the Pioneer Venus Large (PVLP), after decelerating in the Venus atmosphere, initially, a mortar-deployed drogue parachute is inflated. Then, the drogue parachute pulls out the back shell and the main parachute. The drogue is deployed at Mach 0.8 using a g-trigger and timer-based system similar to Pioneer Venus [10]. After its deployment at approximately a 70 km altitude, the drogue parachute deploys the main parachute. The main difference between the Pioneer Venus probe and the DAVINCI is that it uses sub-sonic Disk-Gap-Band (DGB) parachutes instead of conical ribbon parachutes. Even though the DGB parachutes have not flown in the Venus atmosphere before, they have a long flight heritage as they have been used on all Mars missions. In addition, the DAVINCI probe also enters the Venus atmosphere at a much shallower flight path angle compared to the Pioneer Venus probe, allowing it to have significantly lower peak accelerations and heat flux. After slowing down over the Alpha Regio tessara under the main parachute for thirty minutes, Zephyr will jettison the main chute at approximately 40 km altitude and continue to decelerate naturally using the high density of the Venus atmosphere. Thirty minutes after jettisoning the main parachute, the Zephyr will land on Venus' surface. After touchdown, Zephyr may continue to transmit data, but surviving impact is not part of the baseline DAVINCI mission.

The EDL trajectory simulation used for this study uses POST2. POST2 is a generalized point mass, discrete parameter targeting, and optimization program. POST2 was developed leveraging the POST, whose development began in the 1970s. Carrying the POST heritage, POST2 has been significantly improved by incorporating advanced capabilities. POST2 inputs several models including atmosphere, gravity, propulsion, navigation, and many more environments that allow one to simulate various launch, orbital, and entry missions. One can simulate both three degrees of freedom and six degrees of freedom simulations using POST2. POST2 has significant EDL flight heritage as it has been used in the past successfully for several planetary EDL missions, such as Mars Pathfinder [11], Mars Exploration Rovers [12], Mars Phoenix [13], Mars Science Laboratory [14], Mars InSight [15], and Mars 2020 [16].

Figure 2 shows different models that go into the EDL simulation. Every model in the EDL simulation affects the mission performance. The atmospheric model assumed for DAVINCI is particularly of high interest for two reasons. Firstly, the probe spends a significant amount of time in the atmosphere on and off the parachute. Secondly, the current atmospheric models of Venus are developed using limited sparse data from the previous missions. The accumulation of uncertainties in the atmospheric models during the descent can drastically change the probe's trajectory. To this end, this work interfaces each atmospheric model: Venus-GRAM, VCD, and Lorenz based Venus wind model with POST2 to study the descent trajectory sensitivity to the Venus atmosphere. Discussion in the following section will consider each of these atmospheric models in detail.

III. Venus Atmospheric Models

This section discusses three atmospheric models used in this work for comparison. A detailed discussion on the Venus Global Reference Atmospheric Model (Venus-GRAM) is followed by a discussion on the Venus Climate Database (VCD). Finally, this section talks about the Lorenz based Venus wind model used in this work to simulate the Venus atmosphere. This analysis can help one in the design process of the entry probe heat shields, study the aerodynamic forces, and simulate the descent trajectory.

A. Venus Global Reference Atmospheric Model (Venus-GRAM)

Venus' extreme conditions, such as high atmospheric temperatures and pressure, along with the dense atmosphere, make the EDL missions on Venus extremely challenging. In addition to the extreme environment, limited understanding and knowledge of the Venus atmosphere and the uncertain nature of the atmospheric variations cause the EDL design process to be challenging. Using the data from previous missions such as the Pioneer Venus Orbiter, Pioneer Venus large and small probes, and Venera probe data, an engineering-oriented model called Venus-GRAM was developed by NASA, which can model Venus' atmosphere that can be used for analyzing the EDL missions to Venus [5]. Venus-GRAM provides the mean values and variations of the Venus atmospheric properties that facilitate the previously discussed analysis. Taking inputs such as the time, latitude, and longitude, Venus-GRAM can output mean values of several atmospheric properties such as density, temperature, pressure, and winds. Furthermore, Venus-GRAM provides the dispersions of winds and the density of Venus' atmosphere.

Venus-GRAM query from VIRA atmospheric properties such as density, temperature, and winds along with others using Venus International Reference Atmosphere (VIRA) [6]. For a lower atmosphere that ranges from zero to one hundred kilometers altitude, VIRA determines these atmospheric properties as a function of the altitude and latitude data, whereas, for a middle atmosphere ranging from one hundred to one hundred and fifty kilometers, it depends on altitude and local true solar time [17]. Finally, the upper atmosphere ranges from one hundred and fifty kilometers to two hundred and fifty kilometers altitude. VIRA atmospheric data depends on the altitude and the solar zenith angle. The transitioning between these altitude ranges is evaluated by the Venus-GRAM using the averaging techniques. In addition, NASA has developed a model for the Venus thermosphere that extends from two hundred fifty kilometers up to a thousand kilometers and is incorporated within the Venus-GRAM. This model assumes a constant temperature above two hundred and fifty kilometers altitude.

In addition to the mean values, the Venus-GRAM provides one with variations in the atmospheric properties such as temperature, density, and winds. To provide the temperature variations, the VIRA utilizes the mean temperatures computed as a function of altitude. Mean temperatures below a one hundred kilometers altitude are provided using the VIRA data corresponding to latitudes less than 30 degrees. For altitudes between one hundred and one hundred and fifty kilometers, mean temperature values for the variations are provided using the VIRA day and nighttime data. VIRA mean temperature data for solar zenith angle of 90 degrees is used for computing temperature variations between one hundred and fifty and two hundred and fifty kilometers. Venus-GRAM uses several methods to compute the density variations. Using the temperature variation observations obtained from the previous Venus probes and orbiters, Venus-GRAM estimates the density perturbations. Density perturbations of Venus are small, below hundred and twenty-five kilometers, and vary significantly with the zenith angle above hundred and fifty kilometers. The Venus density with respect to the solar activity is negligible and, therefore, is not included in the Venus-GRAM. The zonal and meridional wind dispersions below eighty kilometers are approximated using the VIRA data, and above this altitude, these perturbations are assumed to increase proportionally with the mean winds. This work utilizes the Venus-GRAM within the POST2 tool that allows one to determine the different atmospheric properties of Venus while the probe passes through it during the DAVINCI PFS trajectory simulation.

B. Venus Climate Database (VCD)

Using the statistics of the Venus atmosphere simulations in the state-of-the-art Global Climate Model(GCM) [8], Laboratoire de Météorologie Dynamique (LMD) with the support of the European Space Agency (ESA) has developed Venus Climate Database (VCD) [7]. venus' atmospheric circulation is computed using GCM by accounting for radiative transfer through the gaseous atmosphere, non-local thermodynamic equilibrium (non-LTE), extreme ultraviolet (EUV) heating, conduction, and molecular diffusion in the thermosphere. Furthermore, in these simulations, sub-grid processes such as convection in the boundary layer and non-orthographic and orthographic gravity waves are also considered. VCD, developed using the data from the Venus atmosphere simulations mentioned above, provides the statistics of venus' atmospheric properties, such as temperature, winds, pressure, and radiative fluxes. In addition, VCD also provides an atmospheric composition of Venus for multiple solar extreme ultraviolet (EUV) and cloud albedo conditions (a measure of how much light is blocked by the clouds). To represent the current best knowledge of the Venusian atmosphere using the observations, atmospheric physics, and Venus surface conditions, VCD is extensively validated using the available Venus atmospheric data collected during the probe missions.

The data from the GCM is stored using the Network Common Data Form (NetCDF), developed and distributed by Unidata. The NetCDF libraries to read these data files are available for numerous platforms, including widely used platforms, such as MATLAB. In VCD, the atmospheric data of Venus is stored using the horizontal variables that are longitudes and latitudes at 96 X 97 horizontal resolution. Longitudes are equi-spaced from -176.25 deg to 180 deg in steps of 3.75 deg, and latitudes range from 90 deg to -90 deg in steps of 1.975 deg. The vertical resolution used to store the VCD atmospheric data consists of ninety levels: the first fifty levels correspond to the lower atmosphere below cloud tops, and the last forty levels correspond to the thermosphere. The data from GCM corresponding to one day of Venus, equal to 243 Earth days, is stored in VCD to provide the daily behavior of the atmospheric properties.

The VCD has three EUV scenarios: solar average, minimum, and maximum. Similarly, VCD has three cloud albedo scenarios: standard cloud albedo, low cloud albedo, and high cloud albedo. The solar conditions describe the heating of the atmosphere above one hundred kilometers, which typically varies on an eleven-year cycle. On the other hand, the atmosphere heating rate correlates with the cloud albedo. Using different solar conditions and cloud albedo settings, VCD can provide Venus atmospheric properties over a wide range of realistic scenarios. In addition, VCD performs horizontal and vertical spatial interpolation and temporal variation to provide atmospheric data using the stored data from the GCM.

Furthermore, VCD provides the variability of the atmospheric properties using the Root Mean Square (RMS) error calculated from the GCM data. In VCD, one can inquire about the day-to-day RMS, which represents the variability of atmospheric variables from one Venus day to another. As discussed earlier, one Venus day is 243 Earth days, and therefore, day-to-day RMS provides the variations in venus' atmospheric properties between every 243 Earth days. Alternatively, the hourly RMS provides the variability of the atmospheric variables within one Venusian hour, which is $1/24^{th}$ of the Venus day. These RMS values are computed as a function of the altitude and pressure. VCD also provides variability by adding large-scale and small-scale variability to the mean atmospheric properties. The large-scale perturbations account for the spatial and temporal variability of atmospheric properties such as pressure, temperature, and winds using Empirical Orthogonal Functions (EOFs) over different simulated Venusian days. On the other hand, small-scale variability provides the density, temperature, and wind perturbations due to the upward propagation of small-scale gravity waves.

C. Lorenz Based Venus wind model

In his recent work, Lorenz has developed an analytical wind model of Venus using the previous Pioneer probe data [9]. Unlike the previously-discussed two atmospheric models, which can model different atmospheric properties of venus' atmosphere, the Lorenz based wind model, as the name suggests, is developed to provide the nominal and the variations in the Venus atmospheric winds. The Venus winds dominate the zonal region (East-West) compared to the meridional winds (North-South). The Lorenz Based Venus wind model implemented in this work is an engineering analytical wind model derived using the measured motions of the four Pioneer Venus probes. The variations of the winds in this model are determined using the differences between the four descent probe data. The Lorenz based wind model gives analytical functions to compute nominal, maximum, and minimum winds as a function of the altitude. This model provides winds as a function of altitude from zero to sixty kilometers and assumes constant winds above 60 kilometers altitude. The zonal winds between zero and sixty kilometers are computed as shown below:

$$U(h) = U_0 + U_s(h/60)^{1.5} + U_t(\tan \frac{h}{H_t})^2 \tag{1}$$

here, U(h) is the zonal wind speed in meters per second, where h is the height in kilometers. U_0 is surface zonal wind speed. For the nominal case, this is zero. However, for the minimum and maximum cases, U_0 is -3 and 3, respectively. U_s and U_t are scale speeds and H_t is the scale height. U_s is 80 for the nominal, minimum, and maximum case, whereas U_t is zero for the nominal case and -30 and 60 for the minimum and maximum case, respectively. The nominal, maximum, and minimum values of H_t are 11, 15, and 7, respectively. Similarly, the Lorenz based wind model also gives one the mean and the variations of the meridional winds up to 60 km altitude. The meridional winds can be computed using the equation shown below:

$$V(h) = V_0 + V_s(\tanh \frac{h}{45})^5 \tag{2}$$

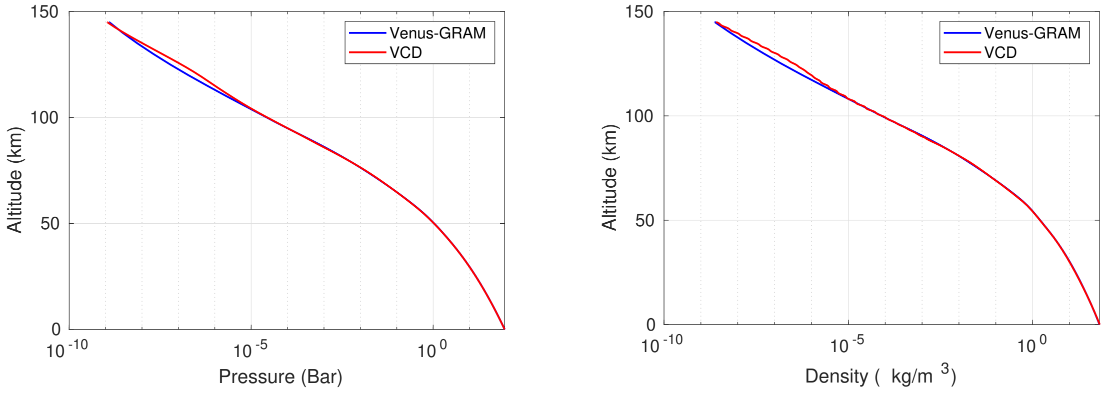
here, V_0 is the meridional speed at the surface, V_s is the scale speed, and V_0 is zero for the nominal case. For the minimum and maximum wind cases, V_0 is -4.5 and 4.5, respectively. Similarly, the V_s are considered -18 and 30 for minimum and maximum wind cases, respectively. The vertical winds are also computed using a similar equation as the meridional winds. W_s and W_0 are zero for the nominal case. For the minimum and maximum wind cases, W_0 is still considered zero. The W_s is considered -1.5 and 1.5 for minimum and maximum wind cases, respectively. In general, the vertical winds have minimal effect on the descent touchdown ellipse dispersions and do not directly affect the probe's horizontal displacement during the descent. It is important to note that the equation for meridional and vertical winds is different from the one proposed in Ref [9] because the model considered in Ref [9] tracks the extremities of a wavy wind profile and is not reflective of what a descent probe would experience.

IV. Venus Atmospheric Model Comparisons

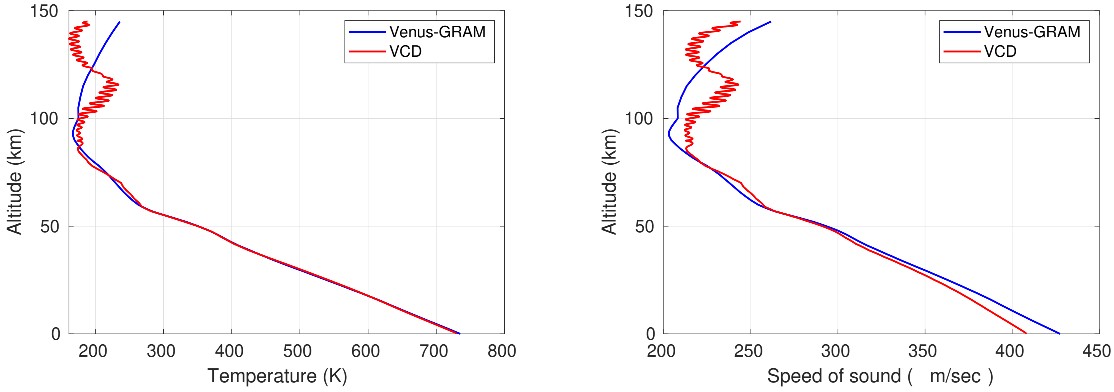
This section compares the atmospheric properties of Venus from Venus-GRAM and VCD, such as temperature, density, pressure, and winds, and their dispersions. For the Venus winds, all three models discussed in the previous section are used, and for the remaining atmospheric properties' comparison, Venus-GRAM and VCD are used. Venus GRAM used in this work is within the GRAM suite. The simulations with the Lorenz based wind model use Venus-GRAM to compute the atmospheric properties such as density, temperature, pressure, and speed of sound.

Figure 3 compares the mean values of different atmospheric properties using the Venus-GRAM and the VCD model. As mentioned earlier, the Lorenz based model is a stand-alone wind model. To this end, the Lorenz based wind model uses Venus-GRAM to compute the other atmospheric properties such as pressure, density, temperature, and speed of sound. From Figure 3, one can see that the pressure and density from the Venus-GRAM and VCD models are very similar compared to each other, especially at the lower altitudes. The temperature data from both models match closely at the lower altitudes and vary significantly at higher altitudes. On the other hand, the speed of sound varies from one model to another at most altitudes. This is because the Venus-GRAM calculates speed of sound from pressure and density, not temperature.

Figure 4 shows the comparisons of the mean zonal (East-West), meridional (North-South), and vertical winds as a function of altitudes obtained using the Venus-GRAM, VCD, and Lorenz based wind model. The mean zonal winds from the Lorenz based wind model are proportional to $h^{1.5}$ up to 60 km altitude and then are considered to be constant. The mean zonal winds from the Venus-GRAM are linearly varying with the height. The mean zonal winds from VCD are more realistic in the sense the wind variations with respect to altitude have variability like one would expect. This is because VCD winds are computed from the data from the GCM simulation. The differences between the zonal winds



(a) Altitude vs. pressure (b) Altitude vs. density



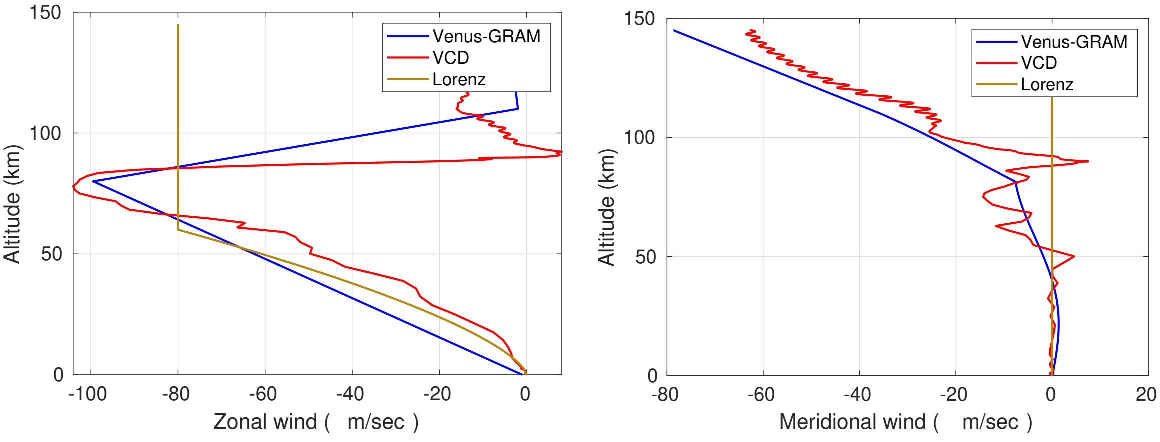
(c) Altitude vs. temperature (d) Altitude vs. speed of sound

Fig. 3 Mean Venus atmospheric properties' comparison between Venus-GRAM and VCD

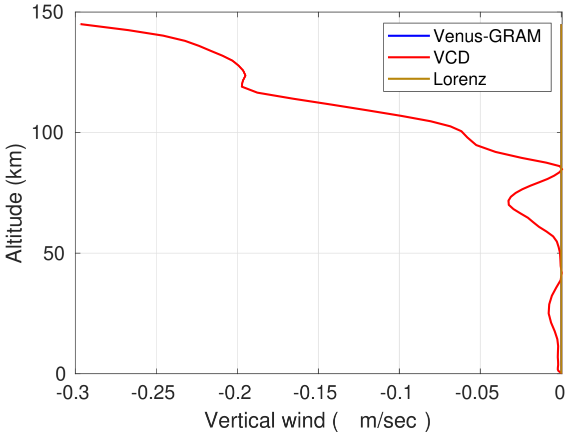
from the three models are significant as they are developed from different data sources. The integrated effect of these differences can influence the trajectory, as seen in the next section. The mean meridional winds are zero from the Lorenz based wind model. The mean wind profiles from the VCD and the Venus-GRAM have similar trends with respect to altitude. However, similar to the zonal winds, the mean winds from the VCD have more variations as one go from one altitude to another. The mean down vertical winds from the Venus-GRAM and the Lorenz based wind models are zero. The mean down vertical winds from the VCD are not zero but are very small in magnitude. In general, because the vertical winds with these magnitudes can be negligible to the probe descent trajectory, this work does not consider the vertical winds for the analysis from here on.

Figure 5 shows the dispersions of different atmospheric properties such as pressure, density, temperature, speed of sound, and the winds obtained from the Venus-GRAM atmospheric model. These dispersions are determined as functions of latitudes and longitudes around the Alpha Regio tesserae.

Venus-GRAM does not provide one with any dispersions for pressure and temperature. The small dispersion that one sees in the plots is due to the variations in the latitude and longitude that result from different initial conditions. Venus-GRAM does provide dispersions in density. The speed of sound and zonal and meridional winds are dispersed significantly. This is because Venus-GRAM calculates speed of sound using density, but not temperature. These dispersions will allow one to account for the uncertainty in the atmospheric model. During the DAVINCI mission, as discussed in the concept of operations, Zephyr spends a significant amount of time about 30 min on parachute (approximately from 70 km to 40 km) and then in free-fall (until the impact) without the parachute for another 30 min, especially in the lower altitudes of the Venus atmosphere. As a result, these uncertainties in the atmospheric models, especially the wind variations, can significantly alter the probe's descent trajectory. To this end, having a larger wind dispersion will provide a more significant uncertainty in the trajectory that might lead to a more conservative mission



(a) Zonal winds (b) Meridional winds



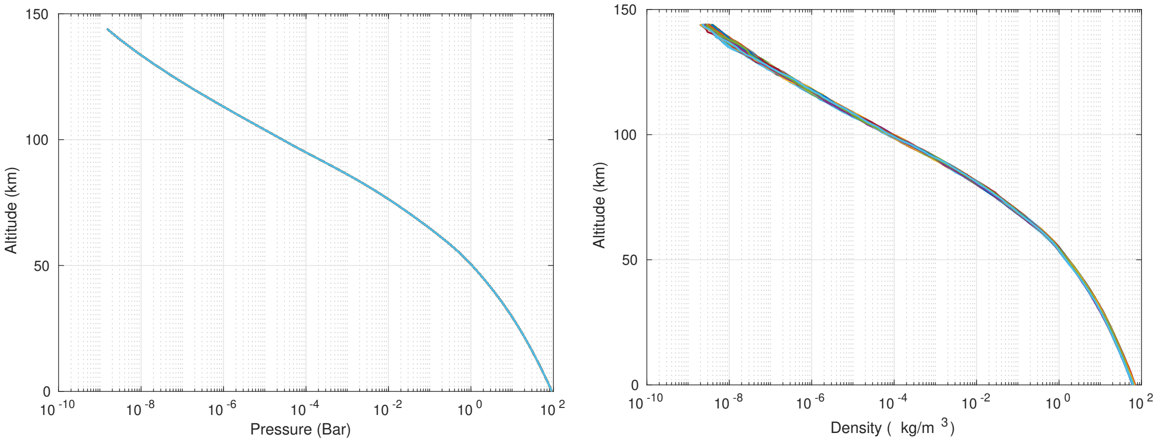
(c) Vertical winds

Fig. 4 Mean Venus atmospheric winds comparison for different atmospheric models

analysis.

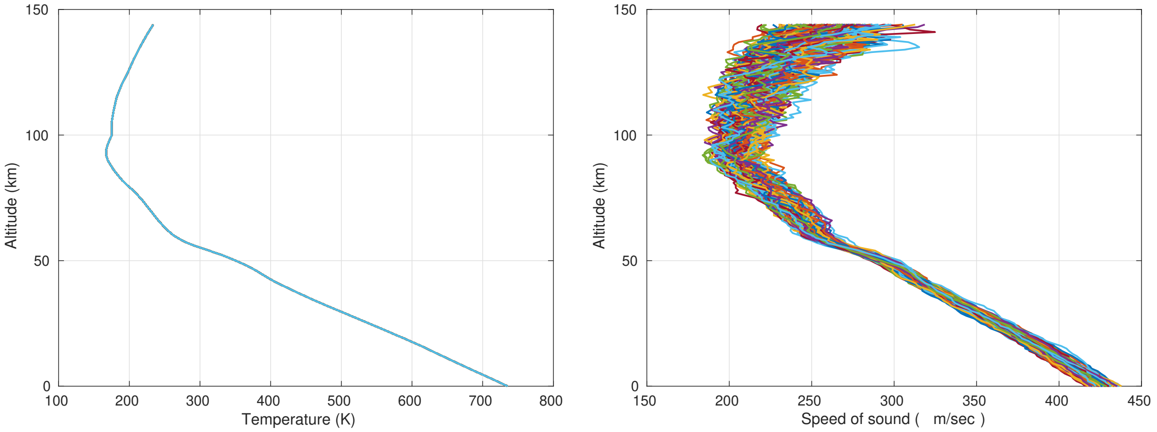
Similarly, Figure 6 shows the dispersions of the Venus atmospheric properties obtained from the VCD. VCD allows one to get these variations by choosing an input option called perturb seed. Randomly choosing this one input from one run to another VCD will provide one with variations. In addition, one can also output additional information such as unperturbed winds and other atmospheric properties, hourly variations root-mean-square error, day-to-day variations root-mean-square error, and many others that can allow one to compute these variations in more than one way. The dispersions of the density are smaller for VCD compared to the Venus-GRAM. Unlike the Venus-GRAM, VCD provides variations in the temperature that are large at the higher altitudes (thermosphere) compared to the lower altitudes (troposphere). The dispersion of the speed of sound, zonal, and meridional winds from VCD is smaller compared to the Venus-GRAM. These dispersions provide one with lesser uncertainty, thus making the trajectory analysis less conservative and less robust.

Figure 7 shows the wind dispersions obtained using the Lorenz based model. As discussed earlier, the Lorenz based wind model only provides the mean and variations of the Venus atmospheric winds. These plots show that the wind dispersions are much larger compared to VCD as well as the Venus-GRAM (See Fig 9 for 3σ profiles). Using these wind profiles for analyzing the probe's descent trajectory through the Venus atmosphere will make our mission analysis much more conservative, as the descent trajectory is sensitive to the Venus wind profiles. For generating these wind profiles, normal distribution is considered for U_0, U_s, V_0, W_0, and W_s within the minimum and maximum values discussed in the previous section. Similarly, the variables V_s and U_t are sampled using the triangular distribution. The variable H_t is sampled uniformly between 7 and 15. As mentioned above, the dispersions of the wind profiles are achieved by sampling different parameters used to compute the nominal wind profile by Lorenz based model. However,



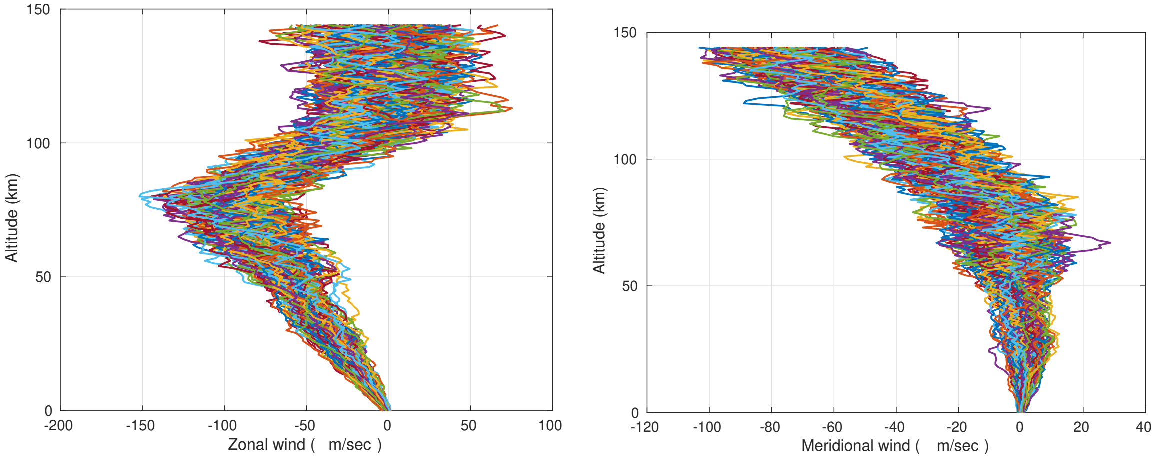
(a) Altitude vs. pressure

(b) Altitude vs. density



(c) Altitude vs. temperature

(d) Altitude vs. speed of sound



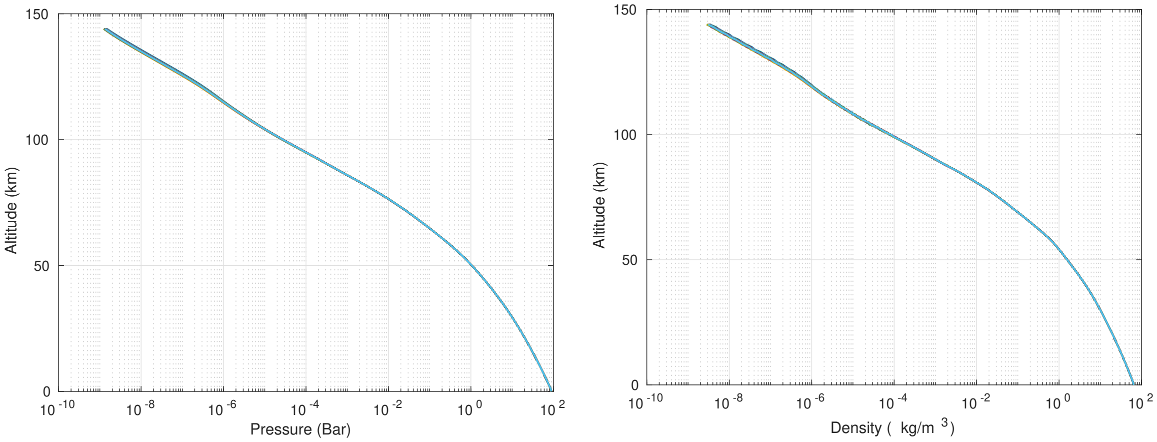
(e) Altitude vs. zonal winds

(f) Altitude vs. Meridional winds

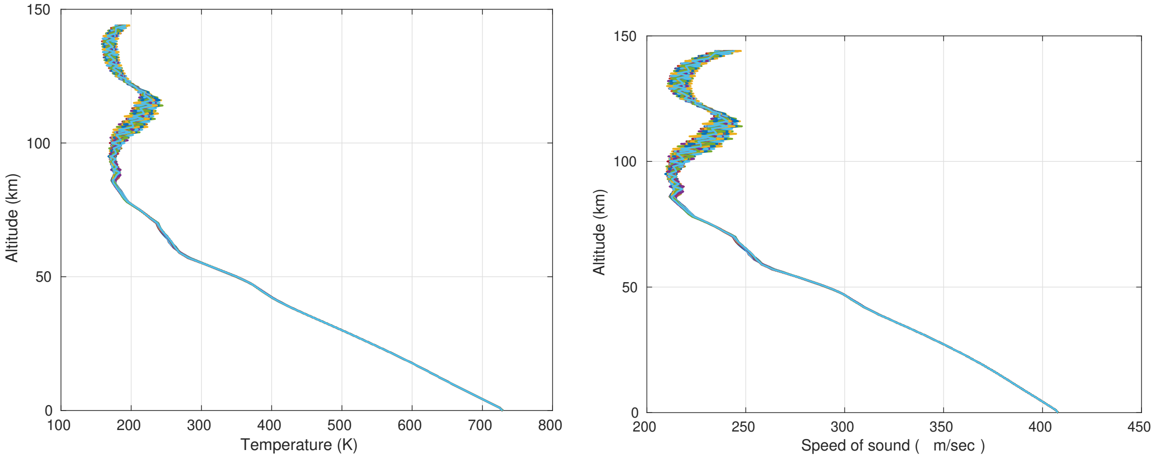
Fig. 5 Venus atmospheric properties dispersions using Venus-GRAM

the authors acknowledge that a new model to disperse the wind profiles is currently under development by Lorenz. As one can see, the wind dispersions using this approach are very smooth and are offsets of the nominal wind profile.

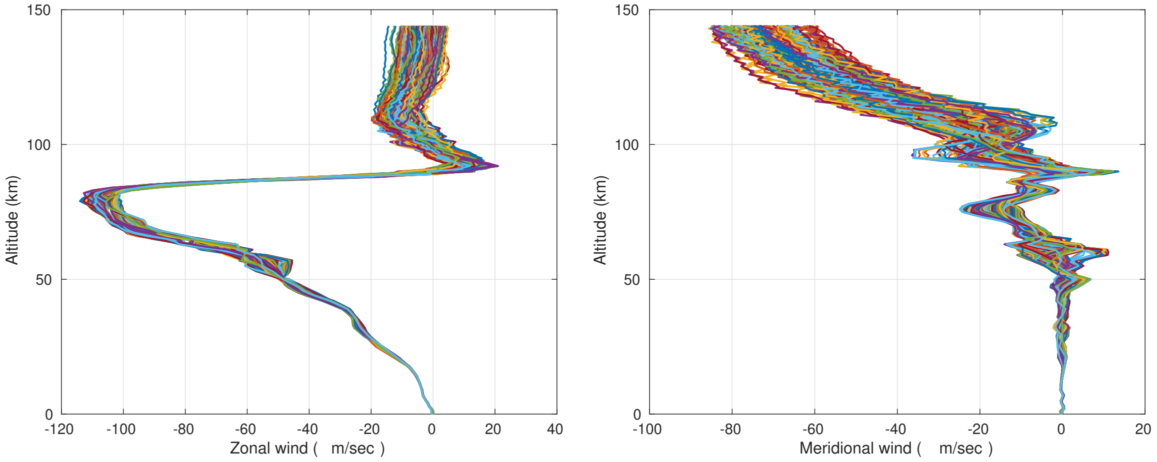
Unlike the wind dispersions from the VCD model, the dispersion of the GRAM model and Lorenz based model are



(a) Altitude vs. pressure (b) Altitude vs. density



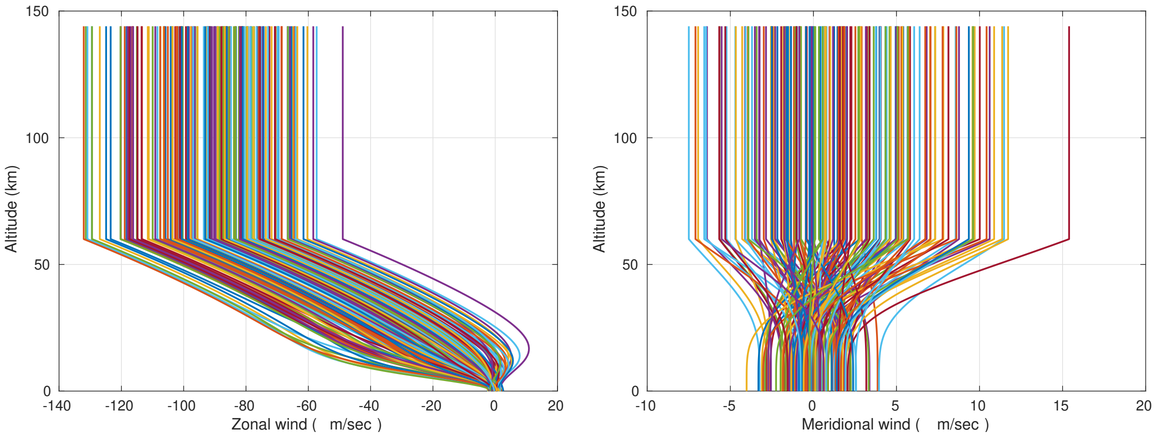
(c) Altitude vs. temperature (d) Altitude vs. speed of sound



(e) Altitude vs. zonal winds (f) Altitude vs. Meridional winds

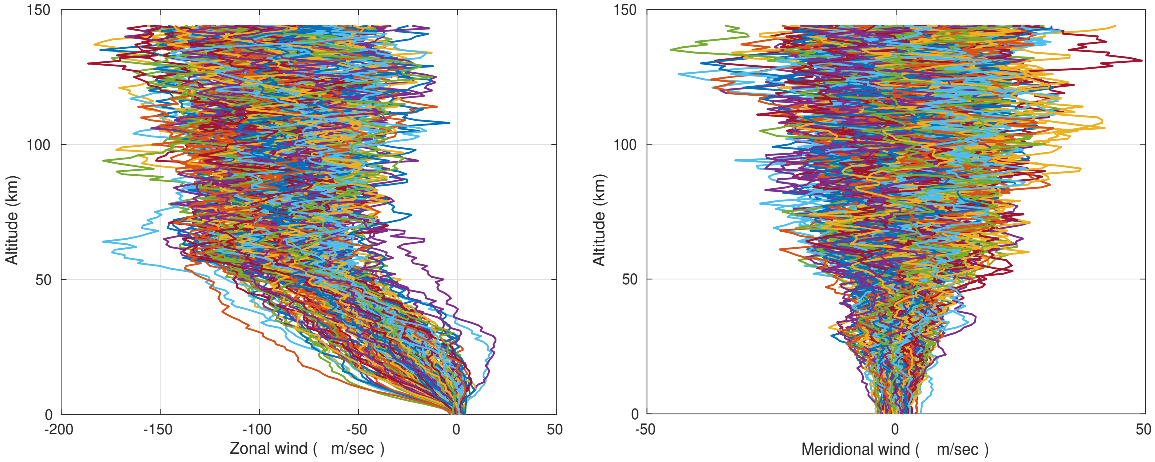
Fig. 6 Venus atmospheric properties dispersions using VCD

more conservative. However, the dispersed wind profiles from the Lorenz based model in the current implementation are smooth. It is useful to have more-realistic wind profiles for the Lorenz based model for probe descent trajectory



(a) Altitude vs. zonal winds (b) Altitude vs. Meridional winds

Fig. 7 Venus atmospheric wind dispersions using Lorenz based wind model



(a) Altitude vs. zonal winds (b) Altitude vs. Meridional winds

Fig. 8 Venus atmospheric wind dispersions using Lorenz based wind model with dispersions from Venus-GRAM model

analysis. Also, the Lorenz based model and the GRAM model are developed using the Pioneer Venus probe data, while Venus GRAM also uses Venera probe data. To this end, the dispersions from the Venus-GRAM model can be applied to the Lorenz dispersed winds to achieve more stressed (more than expected perturbations) dispersions similar to the process used for Mars EDL simulations where the atmospheric profiles have a mean shift and random perturbations superimposed together [18]. Figure 8 shows the wind dispersions achieved using the wind variability from the GRAM model to the Lorenz based model winds. Combining these, one gets wind dispersions larger than the GRAM model. The wind profiles will provide the most conservative analysis. However, these wind dispersions might be too large, especially at the cloud tops. There is extensive data available for winds in these high altitudes from various orbiters, and also, the effect of winds on the zephyr at hypersonic speeds is negligible at these higher altitudes. Also, at lower altitudes, when the zephyr is in free fall, the effect of the winds is significantly reduced compared to when the probe is on the parachute as the reference area is significantly reduced. Using this information, one can have tighter wind dispersions, especially at high and low altitudes, and still keep the analysis conservative. This approach of combining GRAM perturbations with the empirical Lorenz based winds are a stopgap to understand stressing winds for the DAVINCI mission. Future developments where turbulence models are being developed will overcome the shortcomings of this ad-hoc method.

Figure 9 compares the plus 3σ and minus 3σ of the wind perturbations from different wind models with the Pioneer

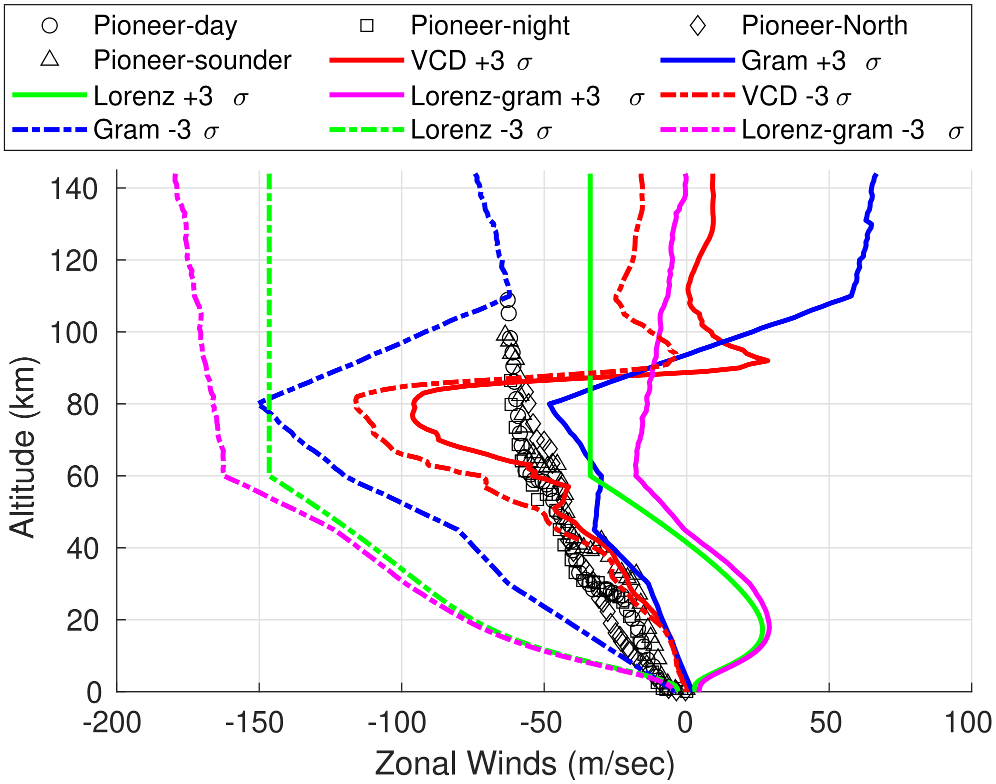


Fig. 9 Comparisons of +/- 3 σ zonal wind profiles from different atmospheric models along with the Pioneer probe data

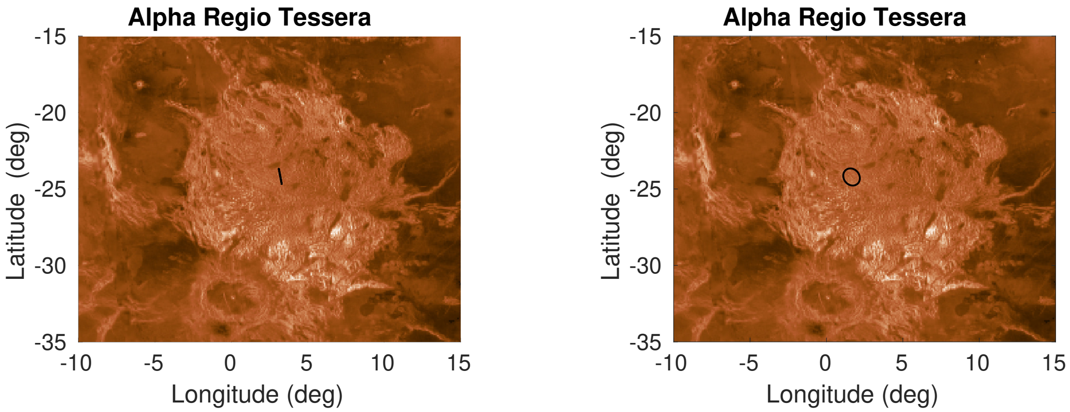
Venus probe data. Note, σ refers to 1-standard deviation of the data. The plus and minus 3σ profiles of each wind model are computed using 8000 Monte Carlo runs. Besides VCD, all of the wind dispersions encompass the Pioneer Venus probe data within +/- plus 3σ profiles. The wind dispersions from the GRAM are much tighter compared to the wind dispersions obtained by applying the wind variability from the GRAM model to the winds from the Lorenz based model. The reason for this is the addition of the wind variability from the GRAM to the already dispersed Lorenz based wind model.

Table 1 Semi-major and semi-minor axis of the 99 percentile touchdown ellipse using different wind models

Wind Model	Semi-major axis (km)	Semi-minor axis (km)	Azimuth of Semi-major axis (deg)
No winds	52.55	0.98	-9.91
Venus-GRAM	60.90	50.13	-25.61
VCD	50.42	6.38	-9.28
Lorenz	157.45	54.19	-89.09
Lorenz + GRAM	165.24	61.81	-89.33

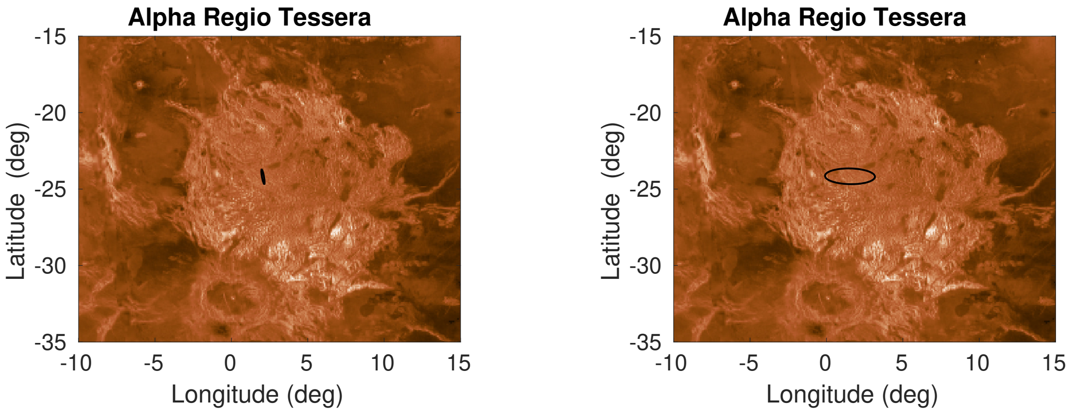
The effect of the atmospheric variability to EDL landing ellipse are computed by using the POST2 simulation of the DAVINCI mission mentioned in Davinci EDL overview section. Additional details of this simulation are discussed in detail in Ref [4].Table 1 shows the semi-major and semi-minor axis sizes of the touchdown ellipse, while Figure 10 shows the 99th percentile touchdown ellipse with no winds and with winds from different atmospheric models generated using the touchdown locations from an 8000-case Monte Carlo simulation. For this paper, the 99th percentile touchdown ellipse will be referred to as the touchdown ellipse.

As one can see from Figure 10, the touchdown ellipse is very small in the case when there are no winds. This small ellipse shows the sensitivity of the descent trajectory with respect to the Venus atmospheric winds. As seen in the



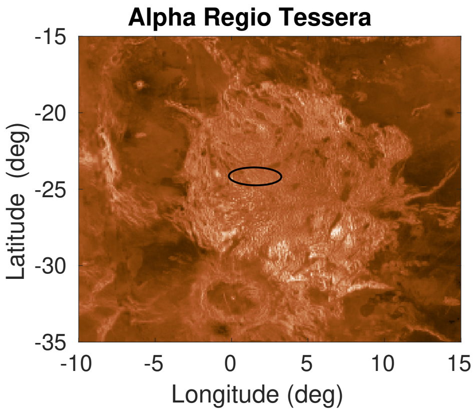
(a) No winds

(b) Venus-GRAM



(c) VCD

(d) Lorenz based wind Model



(e) Lorenz based wind Model with GRAM Perturbations

Fig. 10 Zephyr 99 percentile touchdown ellipse over Alpha Regio tesserae using different wind models

earlier analysis, the VCD winds have smaller dispersions and, therefore, have smaller touchdown ellipse compared to the other two atmospheric wind models (Venus-GRAM and Lorenz based model). The size of the touchdown ellipse is directly proportional to the size of dispersions of the atmospheric winds. Having a larger touchdown ellipse makes the mission analysis more conservative. Lorenz based winds with GRAM perturbations provide the largest touchdown ellipse followed by the Lorenz based model, Venus-GRAM, and VCD. In the landing ellipse of the Lorenz based wind model, the touchdown locations are skewed to the left. This results from using the triangular distribution for V_s and U_s

variables. The magnitude of the zonal winds is much higher than the meridional winds. As a result, the touchdown locations are unevenly distributed more dominantly along the longitude axis compared to the latitude axis. As discussed earlier, using the Lorenz based winds with GRAM dispersions gives the largest landing error ellipse, which provides the conservative solution for some analyses. One can have tighter dispersions using the available data of the Venus atmosphere at higher altitudes and considering the fact that the effect of the winds on the Zephyr is insignificant at hypersonic speeds.

V. Conclusion

This work investigates three atmospheric models for Venus by using them in the DAVINCI mission simulation within the POST2 simulation tool. Specifically, this paper considers Venus-GRAM, the Venus Climate Database, and an engineering wind model based on the Lorenz wind model. The current analysis discusses each model's mean and variations of different atmospheric properties such as temperature, pressure, density and speed of sound. These dispersions of winds from the VCD model are smaller than the wind variability seen in the Pioneer Venus probe data. In comparison, the Venus-GRAM dispersions cover a large range of the variability seen in the Pioneer Venus data, while the dispersions from the Lorenz based wind model are the most conservative and bound the Pioneer Venus atmospheric reconstruction. However, the Lorenz wind profiles are smooth in the current implementation. Future updates of the Lorenz wind model will address this shortcoming, but as a stopgap, this study considered the Venus-GRAM suite atmospheric properties and wind variability applied to the Lorenz based model winds. The criteria for choosing this combination of atmospheric properties and winds is to make the mission analysis as conservative as possible. This work studies the size of the landing error ellipse as a metric to measure how robust the mission design is to change in the atmospheric properties and winds of the Venus atmosphere. The large dispersions from the combined Lorenz based wind model and GRAM model in the current implementation show smaller sensitivity of the mission design to the atmospheric properties and winds. One can make these dispersions tighter without making the analysis less conservative by utilizing the existing Venus atmospheric data available at higher altitudes and identifying the regions where the effect of the winds on the probe trajectory is not significant. The DAVINCI team is currently working on a new wind model for the DAVINCI Mission, allowing one to have conservative mission analysis using tighter wind dispersions.

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