Entry, Descent, and Landing Simulation for DAVINCI

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The Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission is currently scheduled to launch in June 2029 to explore Venus via two flybys and a probe descent scheduled for June 2031. The goals of this mission is to study the origin, evolution, and current state of Venus, especially the deep Venusian atmosphere using an atmospheric probe named Zephyr. The Zephyr will take key measurements in the deep atmosphere of Venus and be the first probe to acquire high resolution Near Infrared digital images below the cloud-deck of a mountainous tesserae surface as it descends over the Alpha Regio highlands region, which could be one of the oldest highland surfaces of Venus. The Zephyr's descent trajectory, which determines the flight over the Alpha Regio, is crucial to meet the science objectives of the DAVINCI mission. To ensure the success of the DAVINCI mission, the Entry, Descent, and Landing (EDL) modeling has undergone several developments to track its trajectory, its uncertainties, and calculate metrics on the science data that can be transmitted. This paper will cover these developments and the current status of the EDL modeling.

I. Introduction

The 2023 Origins, Worlds, and Life, Planetary and Astrobiology Decadal Survey [1] prioritized studying Venus to answer long-standing questions regarding its origin and gas processes in its atmosphere. These questions involve mysteries such as whether Venus was ever habitable in the past, what is the origin of Venus, and why there are extreme atmospheric differences between Venus and Earth despite having similar size and planetary density. In addition, scientists are interested in understanding the atmospheric composition of Venus, how much water the planet may have in the past, and how natural rock formation and erosion occur on the terrestrial planet today [2]. NASA has selected the Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission as the 15th selection of the NASA Discovery Class program to address these long-standing questions regarding Venus' origin using the DAVINCI deep atmosphere descent probe, named Zephyr, together with a carrier relay imaging spacecraft [2] with objectives that include quantifying the chemical composition of the deep Venusian atmosphere. Zephyr will be the first probe to acquire over 40 high resolution Near Infrared descent images under the Venus cloud deck of a mountainous tesserae surface as it descends over the Alpha Regio highlands region, which may be one of the oldest highland surfaces of Venus. The goals are to study the origin, evolution, and current state of Venus, to understand its habitability potential over time, and to create an analog to hot terrestrial exo-planets similar to Venus. The goal of this paper is to cover current and recent modeling and simulation development for the entry and descent phase. As DAVINCI is in an early Phase B state of development, the results discuss in this work may change with future development.

A. Concept of Operations

The DAVINCI mission is currently scheduled to launch in June 2029 and explore Venus via two flybys followed by a probe descent scheduled for June 2031. The spacecraft consists of two elements: the Carrier-Relay-Imaging Spacecraft (CRIS) and the Probe Flight System (PFS). PFS is the entry vehicle which houses Zephyr, the atmospheric descent probe. The Concept of Operations (ConOps) for DAVINCI, shown in Fig.1, begins at the top of the atmosphere at 145 km, where the spacecraft will start its hour-long descent. Approximately three minutes into the entry, the PFS will deploy a subsonic parachute designed to withstand the upper atmosphere of the harsh Venusian environment and exposes the Zephyr to the atmosphere for scientific measurements. After 30 minutes of descent on parachute, the Zephyr

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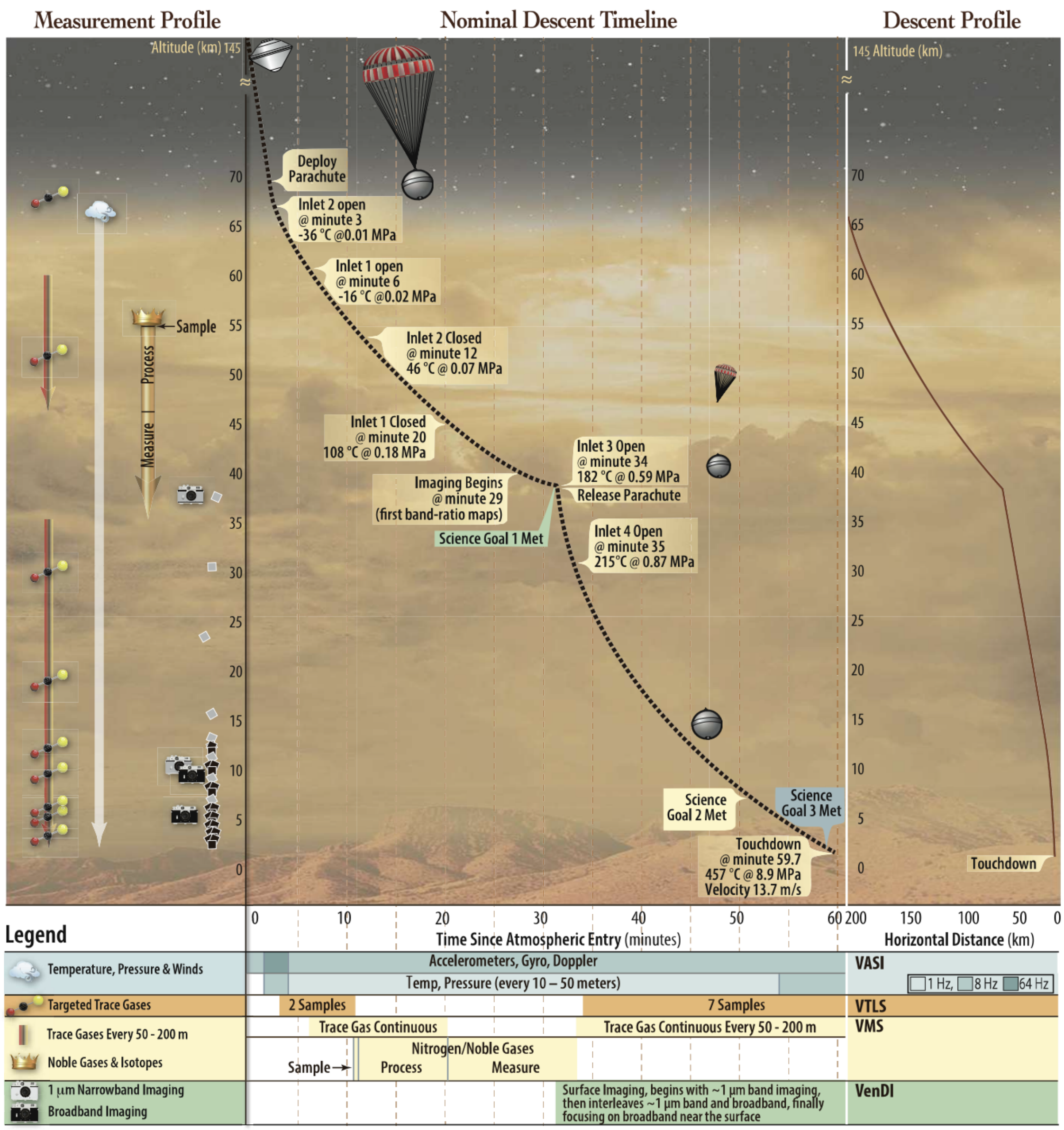
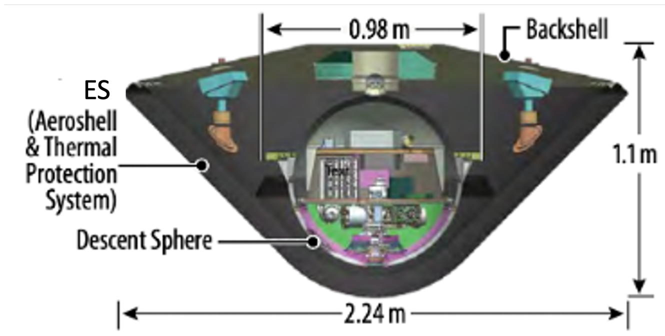
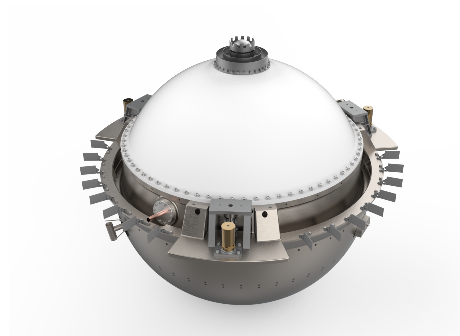


Fig. 1 DAVINCI Entry and Descent Concept of Operations (adapted from Ref. [2])



(a) Entry System [2]. As of 2024, the ES has grown to 2.54 m diameter.



(b) Zephyr

Fig. 2 Components of the Probe Flight System.

will release the parachute near 40 km altitude before the parachute could suffer various damage scenarios from the Venusian atmosphere. The atmosphere of Venus near the surface is approximately 90 times denser than that of Earth, which decelerates the Zephyr further without requiring additional drag from a parachute. During the hour of entry, descent, and landing (EDL), the five science instruments onboard Zephyr will collect invaluable data of the Venus atmospheric composition, environments, and images of beneath the deep cloud layer. The Zephyr descent trajectory determines the touchdown in Alpha Regio, which is crucial to meet the science objectives for the DAVINCI mission. To ensure the success of the DAVINCI mission, the EDL modeling has undergone several developments to track the trajectory, uncertainties, and critical metrics based on operational constraints and scientific requirements.

B. Vehicle System

The DAVINCI vehicle system contains both the PFS and the CRIS. The PFS is the spacecraft that is the EDL vehicle, and itself is comprised of two parts: the Entry System (ES) and the descent sphere, referred to as the Zephyr probe. Fig. 2 shows the two components of the PFS. The full DAVINCI spacecraft supports seven different science instruments, with two instruments in the relay orbiter, CRIS, and five instruments in the EDL vehicle, Zephyr.

As part of the science objectives for the DAVINCI mission, the DAVINCI system will perform two flyby's of Venus as Venus gravity assist maneuvers. The CRIS contains two science instruments: the Venus Imaging System for Observational Reconnaissance (VISOR) and the Compact Ultraviolet to Visible Imaging Spectrometer (CUVIS). The VISOR will take ultraviolet and near-infrared images of Venus in order to help determine their composition and the CUVIS will test new technologies to identify the composition of the upper cloud deck. Since the objective of the EDL simulation is to capture flight performance during entry, VISOR and CUVIS models are not captured in the simulation.

The science instruments on board Zephyr include the Venus Tunable Laser Spectrometer (VTLS), which will measure the key isotopes of sulfur, oxygen, and carbon within in the Venus atmosphere, the Venus Mass Spectrometer (VMS), which will study the noble gases and trace gas makeup of the surface from 67km down to the surface, the Venus Atmosphere Structure Investigation (VASI), which will measure the pressure, temperature, and wind speed through the Zephyr's descent, the Venus Descent Imager (VenDI), which will take infrared images of the Alpha Regio region to study the topography, morphology, and composition of the surface, and the Venus Oxygen Fugacity (VfOx), which is a student experiment to measure the mixing ratio of oxygen in the lowest part of the atmosphere. Some of these instruments are identified in Fig. 3.

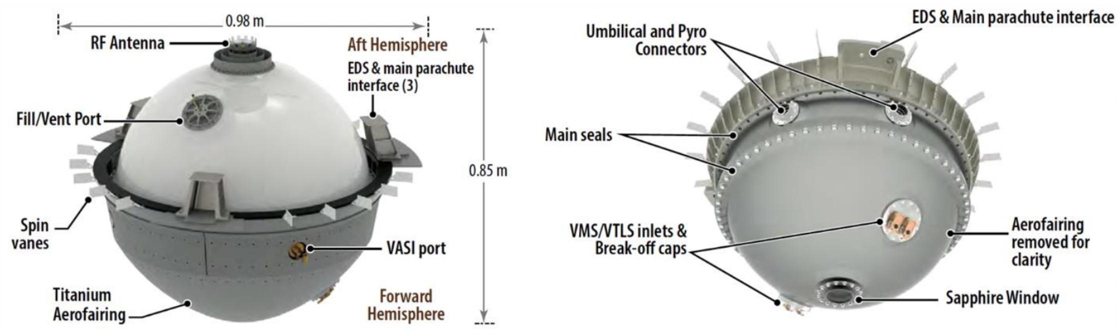


Fig. 3 The Descent Sphere - Zephyr - and its instrumentation [2].

II. EDL Simulation

End-to-end testing of all of the DAVINCI EDL activities on Earth is challenging, especially due to the extreme Venus atmosphere, where the surface temperature can range up to 900° F. In planetary missions, the end-to-end testing at higher fidelity flight environments is often limited to software-in-the-loop simulations, where higher fidelity models of the planetary environment can be modeled and the vehicle design can be analyzed by computationally expensive methods, such as Monte Carlos, to capture performance statistics and test for anomalies [3]. The "L" chart often used to describe the various venues needed for flight system and dynamics testing is shown in Fig. 4. No one avenue can capture the high-fidelity environment expected on Venus while also capturing the intricacies of the flight system, such as hardware timing and requirements. for increasing flight environment maturity, flight dynamics tools (e.g. POST listed in the figure) are used.

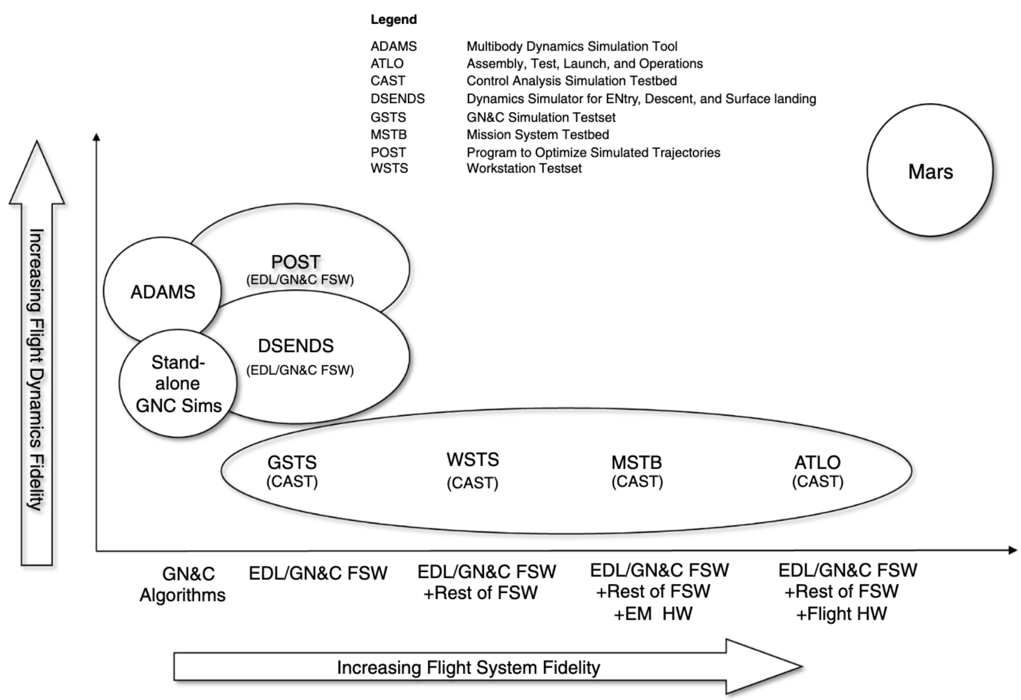


Fig. 4 The "L" chart used during verification and validation of flight projects at various flight dynamics and system testing venue. Example is from Mars Science Laboratory for Mars [3].

The EDL flight dynamics simulation used for this study uses Program to Optimize Simulated Trajectories II (POST2). POST2 is a generalized point mass, discrete parameter targeting, and optimization program. POST2 was developed leveraging the original POST, whose development began in the 1970s to support the Shuttle program. Since then, POST2 has been significantly improved by incorporating advanced capabilities that allow for fast, high-fidelity trajectory simulation, while also conducting uncertainty quantification via Monte Carlo simulations [4]. POST2 has significant EDL flight heritage, as it has been used as the prime simulation in the past successfully for several missions, such as Mars Pathfinder [5], Mars Exploration Rovers [6], Mars Phoenix [7], Mars Science Laboratory [8], Mars InSight [9], and Mars 2020 [10].

POST2 integrates various models, including atmosphere, gravity, propulsion, and navigation, that can be used to simulate various unique launch, orbital, and entry missions. Both three and six degrees of freedom can be simulated using POST2. Fig. 5 shows the various models that are part of the simulation. Many of these models are described at length in Sec. III.

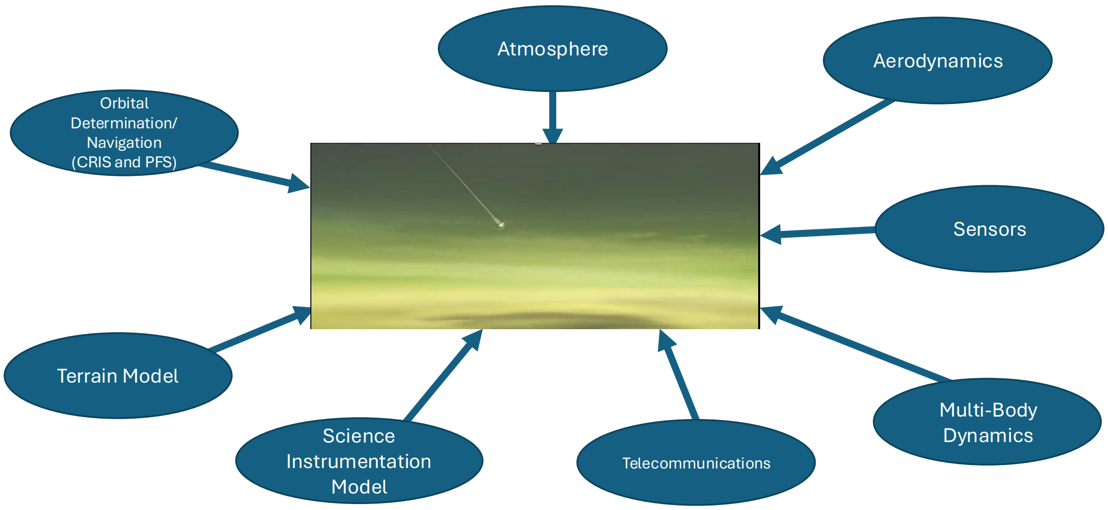


Fig. 5 Models used to simulate entry and descent modeling for the DAVINCI atmospheric flight phase.

III. Models

The POST2 simulation for DAVINCI is used to design the trajectory during the EDL portion of the mission. Additionally, the sequences used by the spacecraft to trigger configuration changes and science instrumentation measurements are informed by the timing of several events, such as heatshield jettison, reaching below the cloud layer, parachute jettison, and touchdown, from the simulation. Thus, it is critical that the simulation incorporates the proper physics to provide realistic times for vehicle design. Key among these models are atmosphere, aerodynamics, multi-body dynamics between the parachute and the Zephyr, data relay, data prioritization, and science instrumentation modeling, which are covered in this section.

A. Atmosphere

Capturing the trajectory requires a good understanding of the flight environment. On Venus, the large scale height of the atmosphere and the strong winds in the mid-altitudes, where the Zephyr is on parachute, have a strong influence on the vehicle dynamics. Ref. [11] investigated the effects of various models on EDL metrics of interest, such as landing ellipse size, and had found that atmosphere affected a significant portion of the performance.

Data needed for accurately modeling the Venus atmosphere for Venus atmospheric parameters are rather sparse, largely coming from Pioneer Venus, Venera, and Vega missions. The standard atmosphere for Venus is the Venus International Reference Atmosphere (VIRA), which was presented in a special edition of a journal [12], and Ref. [13] and leveraged the past American and Soviet missions though the 1980s. These data sets have been incorporated into the Venus Global Reference Atmospheric Model (Venus GRAM) [14] and is used by POST2 for modeling atmospheric properties.

The timeline for DAVINCI exposes the Zephyr to the Venus atmosphere for more than 50 minutes, with 30 minutes of the flight under parachute. The Venusian atmosphere slows than the vehicle to subsonic conditions early in the EDL

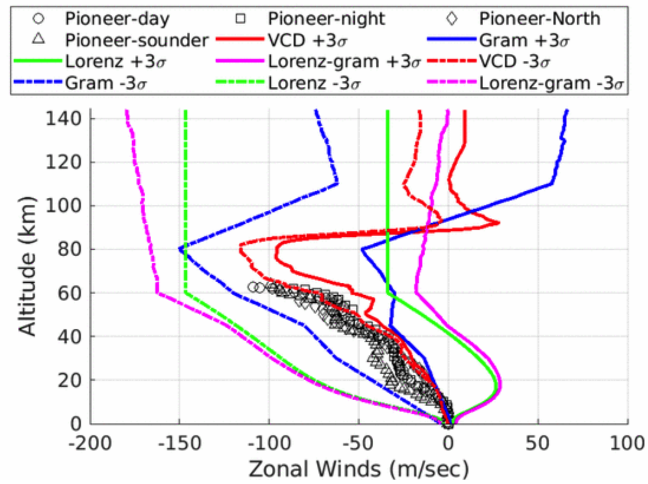


Fig. 6 Comparison of zonal winds from various Venus atmospheric models and flight data (from Ref. [17])

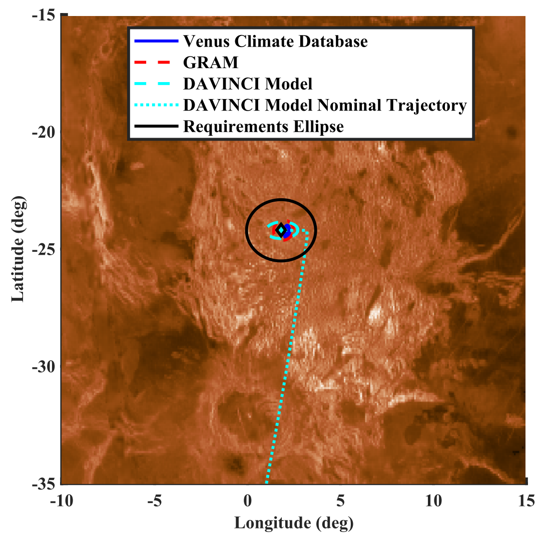
trajectory, such that the vehicle will be susceptible to winds for a prolonged period of time. Thus, the choice of the wind model has a big effect on vehicle dynamics and performance assessments.

VenusGRAM and other global reference models like the Venus Climate Database (VCD) [15] can provide different wind models. However, past studies have shown that generalized wind models may not be conservative enough when trying to accurately predict metrics such as a landing ellipse. Ref. [16] constructed a wind model bounding the observable flight from the Pioneer Venus mission. A comparison of the envelope model created by Ref. [16], VCD, and VenusGRAM can be seen in Fig. 6. The figure focuses on the dominant zonal winds (East-West), and has a large effect on the vehicle trajectory.

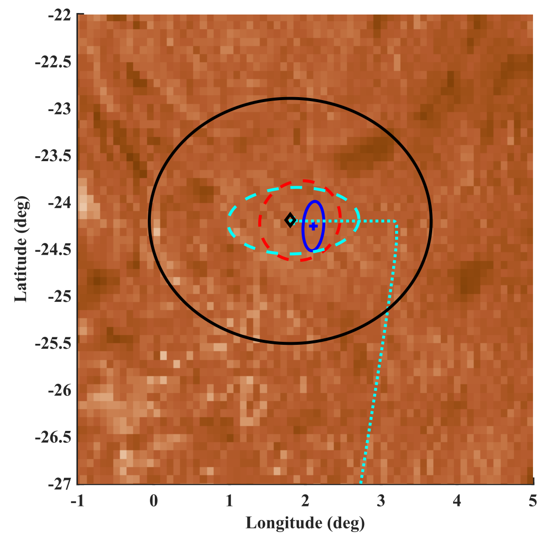
Prior analysis has shown that the global reference atmosphere models often do not create bounding landing area estimates [16]. For an EDL mission, a key flight performance metric involves estimating the possible landing area that is based on a required confidence interval. An example of this is shown in Fig. 7, where the relative size differences of the ellipses are driven by the unique wind models previously described. When the trajectory simulation uses Venus Climate Database and VenusGRAM, the landing areas are smaller than the Lorenz model, where the wind estimates encapsulate historical Venus probe data. The project has chosen to use the model from Ref. [16] as the simulated wind model for DAVINCI as it is the most conservative. Note, all wind models predict a landing area that satisfies the landing requirement based on science needs.

Fig. 7 also shows the nominal trajectory of the vehicle. For the current DAVINCI mission design, the vehicle approaches the Alpha Regio tesserae from the South. However, the figure shows a 90 ° turn taken around 3° longitude and -25.25° latitude which is due to the strong zonal winds (shown in Fig. 6) around the altitude of parachute deployment near 70 km altitude. This observation has been captured in the past (Ref. [16]) and is an unique feature of Venus probe trajectories caused by the planet's strong zonal winds at the mid-altitudes.

The 30 minutes of parachute flight and followed by 30 minutes of free-fall also makes the probe attitude susceptible to gusts of winds. The probe must maintain a direct line of sight with the CRIS in order to telemeter the science data, which can be affected by these strong gusts. An as yet unpublished turbulence model has been developed to capture the effects of gust during descent. The gust is a higher frequency noise that is added on top of the mean winds and is based on probe and balloon data from historical Venus missions. The prescription is similar to the Titan turbulence model developed for the Dragonfly mission and discussed in Ref. [18].



(a) Landing Ellipse over Alpha Regio



(b) Zoomed In Landing Ellipse

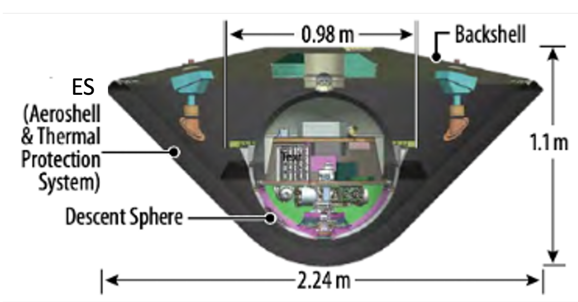
Fig. 7 The 99%-tile confidence interval landing area prediction of the DAVINCI spacecraft based on various wind models.

B. Aerodynamics

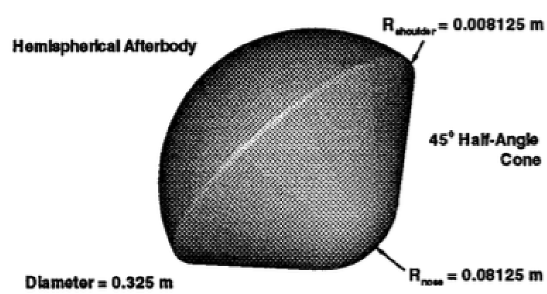
The aerodynamics for the DAVINCI EDL spacecraft can be broken into two phases: entry aerodynamics, where the aeroshell flight encompasses rarefied, hypersonic, supersonic, and transonic regimes. This leads to the descent phase, first on parachute and then in free-fall, where the vehicle exposed to the flow is the Zephyr.

1. Entry

The entry aeroshell for DAVINCI is a 45° sphere-cone, similar to past U.S. Venus missions, such as Pioneer Venus and the Mars Microprobe. Fig. 8 shows the similarity in the forebody geometry between DAVINCI and Mars Microprobe, and was the original justification behind using the Mars Microprobe aerodynamic model for initial entry [19].



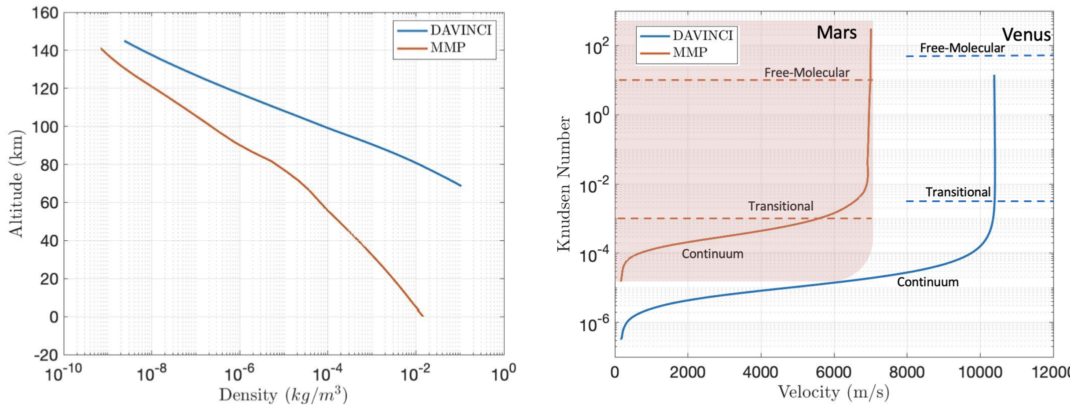
(a) DAVINCI Entry Vehicle [2]. As of 2024, the ES has grown to 2.54 m diameter.



(b) Mars Microprobe Entry Vehicle [20]

Fig. 8 Comparison between Mars Microprobe and DAVINCI's entry vehicles.

However, the difference in the trajectory space between what was used for Mars Microprobe aerodatabase development and the DAVINCI trajectory, as seen in Fig. 9, led to a reconsideration of the assumption of using the Microprobe aerodatabase. Another crucial difference was the backshell geometry between Microprobe and DAVINCI, which could be influential in the transonic regime prior to parachute deploy around Mach 0.8.



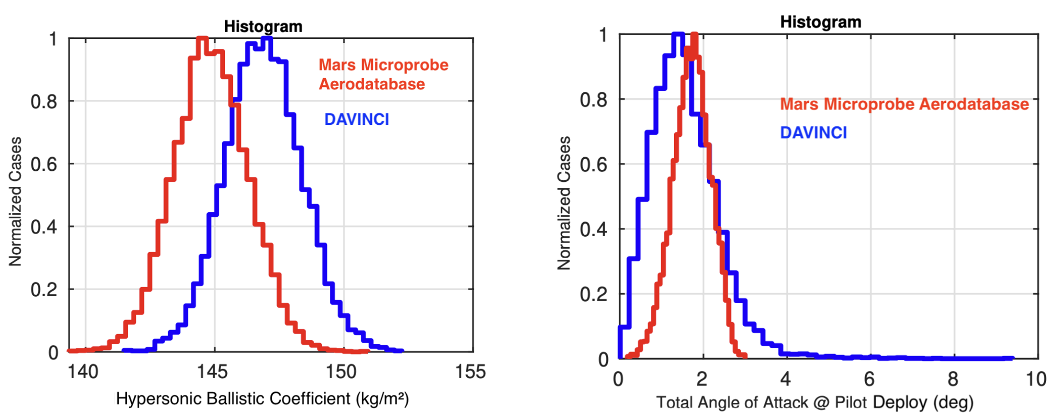
(a) Altitude vs. Density

(b) Knudsen Number vs. Velocity

Fig. 9 Comparison between Mars Microprobe and DAVINCI design entry trajectory profiles.

Due to the significant differences in the trajectory space and backshell geometry, the DAVINCI aeroscience team developed a tailored aerodynamics model based on DSMC and CFD solutions. The details of the aerodynamics model is still unpublished but will be presented in the future.

Upon using the aerodatabase, changes in two significant metrics for the DAVINCI flight performance were noted. The first noted metric was a change in ballistic coefficient during the entry phase due to differences in the axial force coefficient in the new aerodatabase when adjusted for flight at Venus conditions, as seen in Fig. 10. The second metric involved the overall dynamic stability of the vehicle and its affects on angle of attack at parachute deployment. The flight performance of the vehicle remained within requirements.



(a) Aerodynamics during Entry

(b) Attitude at Parachute Deploy

Fig. 10 Effect of entry aerodatabase on DAVINCI performance.

2. Descent

The Zephyr is expected to be exposed to the Venusian atmosphere for 55 minutes of flight and is in free-fall for 30 minutes of that flight. The trajectory of the Zephyr is during incompressible regime of flight, and the Reynolds Number is turbulent, primarily due to the high viscosity of the Venus atmosphere. Fig. 11 shows the Mach Number and Reynolds Number trajectory space of the Zephyr along with the trajetory space of some experimental test data the DAVINCI project has collected to characterize the aerodynamics of the vehicle. The test data include a helicopter drop test at the Utah Test and Training Range (UTTR), wind tunnel tests at NASA Langley Research Center's Vertical Spin Tunnel (VST), and at Langley's the 12-ft Low Speed Wind Tunnel. Ref. [21] discuses the challenges and limitations of

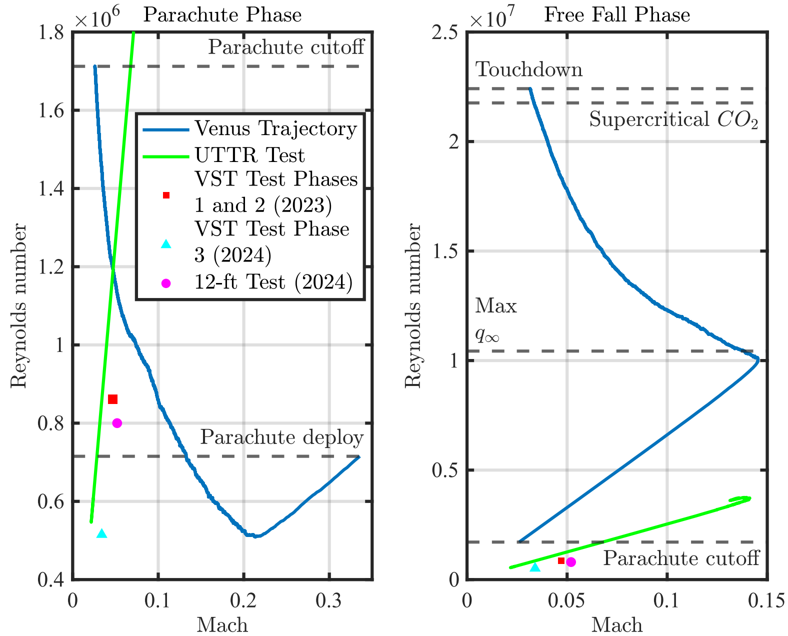
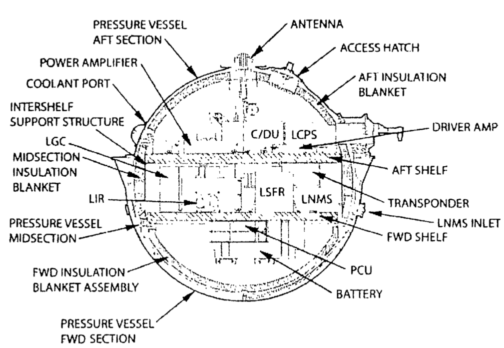


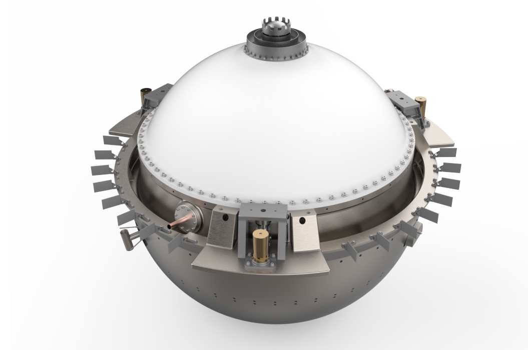
Fig. 11 Mach Number and Reynolds Number regime of the DAVINCI Zephyr trajectory (from Ref. [21])

performing experimental tests in this trajectory space.

Nevertheless, experimentally driven data continues to be one of best sources of data for characterizing the Zephyr aerodatabase. Current CFD capabilities are limited when resolving the flow over complex objects (such as the Zephyr with its drag plates and spin vanes as seen in Fig. 2(b)) [21]. The project initially used an aerodatabase developed for the VISAx concept created in 2010 based on Pioneer Venus flight data and some wind tunnel data [22]. Despite the general similarities between the DAVINCI Zephyr and the Pioneer Venus Large Probe's Descent sphere, as seen in Fig. 12, there are still large differences in the outer mold line of the vehicle, such as the placement and size of the instruments, the shape of the drag plates, and the number of the spin vanes. Previous missions have shown that a small difference in outer mold line can lead to large differences in vehicle performance, such as the opposite roll rate observed on the Huygens probe than intended due to a small antenna [23]. Thus, the differences between Pioneer Venus and the Zephyr meant that DAVINCI requires its own individual descent aerodatabase.



(a) Pioneer Venus Large Probe (from Ref. [24])



(b) Zephyr

Fig. 12 Comparison of the Pioneer Venus Large Probe and Zephyr outer mold line.

The current DAVINCI descent aerodatabase consists of axial, normal, and side force coefficients as well as pitching and yawing moment coefficients. The rolling moment coefficient model, still being developed, will be similar to the model described in Ref. [21]. Additionally, some dynamic coefficients such as pitch and yaw damping are defined, but the roll damping model is still under development. The data from a series of VST and 12-ft tunnel tests conducted at NASA Langley in 2023 and 2024 are the source for the aerodynamic coefficients. Upon implementation of the new aerodatabase, one observation has been that the new aerodatabase predicts larger axial force coefficient than the previous database described in Ref. [22]. One result is that the drag plate size could be reduced to decrease the axial force coefficient, bringing performance quantities such as total descent time (as seen in Fig. 13) closer to what was predicted with the older aerodatabase (and flight requirements).

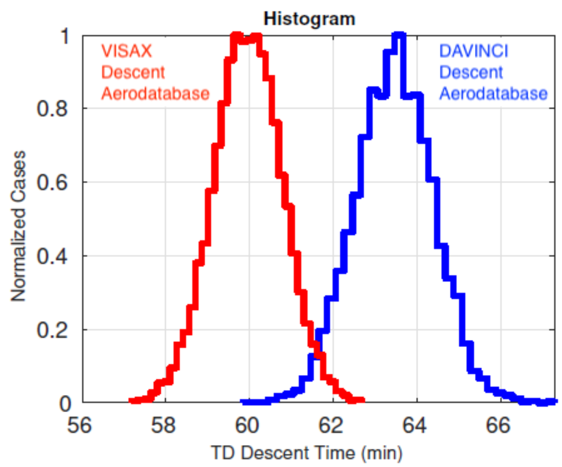


Fig. 13 Change in descent time with the new DAVINCI descent aerodynamics model

C. Multi-body Dynamics

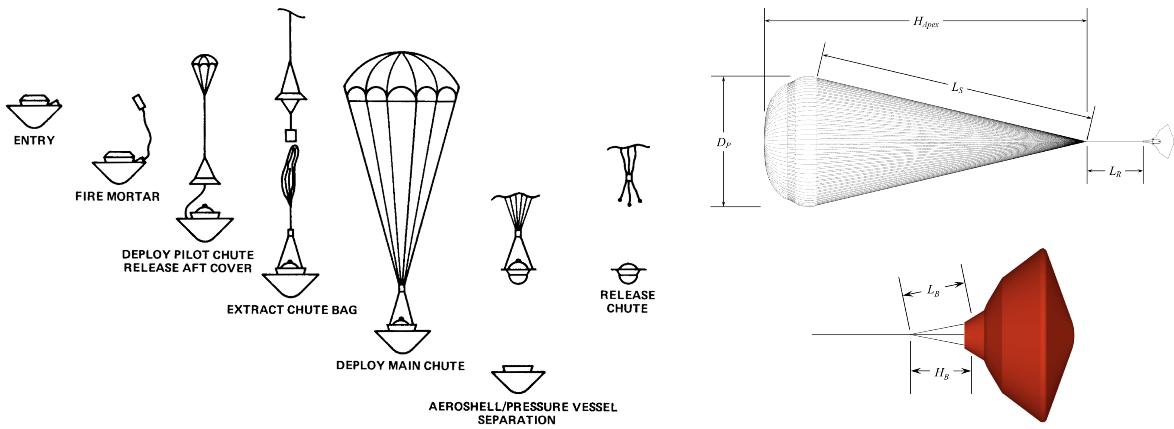
The DAVINCI EDL sequence has two parachutes – pilot parachute and the main parachute – where the spacecraft is under the main parachute for 30 minutes of flight. During this phase of flight it is critical to model the dynamics that affect the ability of the vehicle to maintain a line of sight to the relay orbiter for data transfer. This work focuses the discussion on the highly dynamic phases seen during initial deployment and main parachute separation.

1. Deployment

Fig. 14 shows the concept of operations for parachute deployment for DAVINCI (based on the Pioneer Venus design) as well as the specific diagram of the multi-body model. The pilot parachute is mortar-deployed based on a g-trigger that senses the acceleration pulse at a few fixed points in the trajectory and then deploys the parachute at a time based on a polynomial defined based on pre-flight modeling data. The g-trigger logic is similar to what has been used on Pioneer Venus [25] and Stardust [26]. The pilot parachute is deployed at approximately Mach 0.8 and then 5 seconds later, extracts the main parachute by a 5 second timer. Finally, the heatshield is separated exposing the Zephyr to the flow for science observations.

Both the pilot and the main parachute consist of a canopy, suspension lines (L_s), riser line (L_R), and three bridle lines (L_B) attached to the main vehicle. The schematic of a parachute is shown in Fig. 14(b) although the payload in the figure is another aeroshell, not DAVINCI. The vehicle also labels the diameter of the parachute (D_P) which is used in aerodynamic calculations. In past EDL simulations [27–29], the parachute and the payload (whether aeroshell or the descent sphere) are modeled as separate rigid bodies connected by the three elastic bridle lines. Even though it is hard to envision a parachute as a rigid body, this assumption is useful when simplifying the multi-body dynamics that occur during and post-deployment. The model used is shown in Refs. [27–29].

The DAVINCI current parachute system uses a Disk-Gap-Band parachute design with the pilot parachute approximately 2.5 meters in diameter and the main parachute approximately 6 meters in diameter.



(a) Parachute Concept of Operations [24]

(b) Multi-body Diagram [27]

Fig. 14 Multi-body parachute modeling concept of operation and diagram.

2. Separation

At the completion of the parachute phase, the Zephyr separates from the main parachute and descends in free-fall to the Venusian surface. The parachute is connected to the descent sphere via a three bridle lines (triple bridle) that are attached to parachute attach towers on the Zephyr drag plates. Pparachute separation occurs during key science data collection and transmission time period, so maintaining the pointing angle to the relay orbiter is critical. However, since the separation event involves cutting of the bridle lines by NASA Standard Initiators (NSI), it is possible to induce imbalanced moments on the vehicle by asynchronous cutting. The effect of a 3 millisecond or a 9 millisecond difference between the first and last NSI firing on the vehicle attitude is captured in Fig. 15. The cause of this asynchronous cutting can be due to both hardware and software limitations; the cutters are certified to fire to a specific timing precision. In order to provide redundancy, two signals will be sent to the cutters. If the second signal were to be sent after the first signal, then the delays can be up to a 100 milliseconds if the first signal does not properly fire the NSI.

As can be seen, the more asynchronous tipping case (9 milliseconds delay) results in significantly higher pitch rates and pitch angles. In the same hand, the more benign case (3 ms delay) produces angles that are less likely to cause a drop in the connection as the angular excursion will results in lower pointing angle error. In both cases, these disturbances are shown to damp out within 20 seconds of parachute separation. One mitigation strategy for the data relay due to the pitching motion is to pause the uplink for a few seconds around the parachute separation event.

Modeling the parachute separation effect has been done by assuming that the parachute forces are applied asynchronously to the vehicle. While on parachute, the forces are applied equally through all three bridle lines. Then, one or two of these lines is cut and the same force is then redistributed through the other lines. After a short delay, the remaining lines are cut and the descent sphere falls freely without any parachute effects acting on it. This modeling assumes that the bridle lines are rigidly attached to the parachute attach points. It is recognized that the rigid connection line assumption is a conservative modeling assumption, and future work will look at the effects of modeling an elastic calculation to refine this analysis. The above analysis was conducted with a preliminary model of the parachute system. Future analysis will update these results based on the finalized DAVINCI parachute design as well as any multi-body parachute design tuning needed for conditions at Venus.

D. Data Relay

In order to track the science metrics for the DAVINCI mission, a series of telecommunications calculations that run in the simulation has been implemented. POST2 contains a heritage telecommunications module used on Mars Science Laboratory [30], Mars InSight [31], Mars 2020 [32], and the upcoming Titan Dragonfly mission. For the DAVINCI mission, additional functionality has been added The most significant change is the implementation of an adaptive data rate (ADR) as a function of signal strength.

From atmospheric entry to heatshield separation, the data rate is initialized at a fixed 500 bits per second (bps). After heatshield separation, the ADR feature is initiated. ADR establishes a handshake between the probe and the

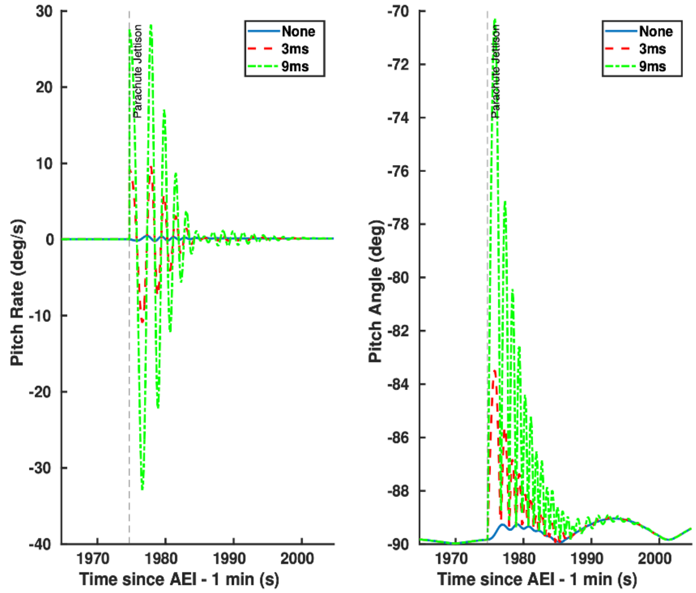


Fig. 15 Effect of asynchronous cutting time of the parachute bridles during parachute separation on Zephyr attitude.

relay orbiter, and as long as the signal strength is strong, the data rate can be incrementally increased. ADR offers an advantage over fixed data rates as it allows the data rate to be a function of trajectory conditions. For example increasing the data rate when the range between relay and probe is decreasing, while reducing the rate when the range is increasing.

For DAVINCI, ADR is set to 2 kbps after heatshield separation and then changes with the vehicle trajectory. The data rate (D) is calculated from 1, which is a function of the signal-to-noise ratio (P_t/N_0). For non-fault cases, the data rate after ADR initialization is not fixed. To calculate the new data rate, the P_t/N_0 is sampled every 10 Hz and, if the signal strength is maintained, the effective P_t/N_0 used grows by a fixed amount and then will hold that new value for 1 second. Additionally, a decibel (dB) margin is applied as an adder to the P_t/N_0 value.

$$D = 10^{\frac{(P_t/N_0)_{used} - Margin}{10}} \tag{1}$$

A notional result of this data rate model is shown in 16. As the PFS descends through the atmosphere and the CRIS, reaches its periapsis while flying over Alpha Regio, the data rate increases. The steps shown are caused by the algorithm maintaining the current signal-to-noise ratio for a minimum time before growing. When the PFS descends further into the atmosphere where the signal-to-noise ratio decreases due to atmospheric attenuation and CRIS begins to approach the horizon, the data rate accordingly decreases. The adaptable rate allows the PFS to transmit much more data than otherwise possible if a pre-planned fixed rate telecommunication strategy is implemented. It is also beneficial for the uplink rate to start at a lower link rate and increase steadily. Note that the ADR model is still under development and the current description is reflective of the design in 2023 and 2024.

Finally, it should be noted that this model adapts to unforeseen drops in connection. Should the link be broken temporarily, the algorithm will decrease the data rate accordingly and the data rate will have to be increased slowly by a fixed amount once per second. Such an event may result in less data being transmitted than could be, but also provides some robustness that the system will still transmit some data that it thinks it can, rather than assuming a constant data rate when there is a drop in connection. For that reason, it is imperative to understand the sensitivities of the PFS trajectory and robustness of the connection.

E. Data Prioritization

The DAVINCI spacecraft has no requirements to operate post-touchdown, and hence it is important to capture important science data and then transmit the data in the 55 minutes of flight time as the vehicle may not transmit any data after impact on the surface. However, several instruments described in Sec. I.B are competing for the limited

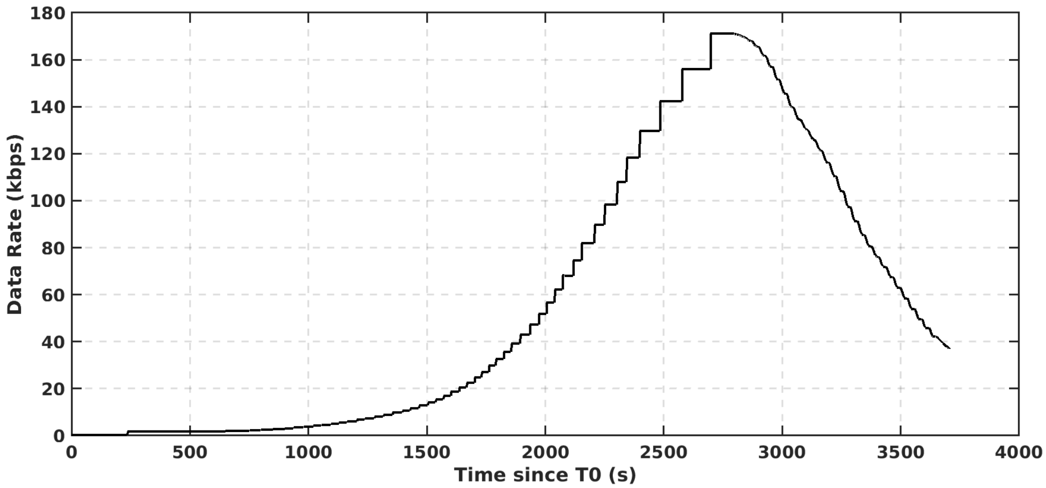
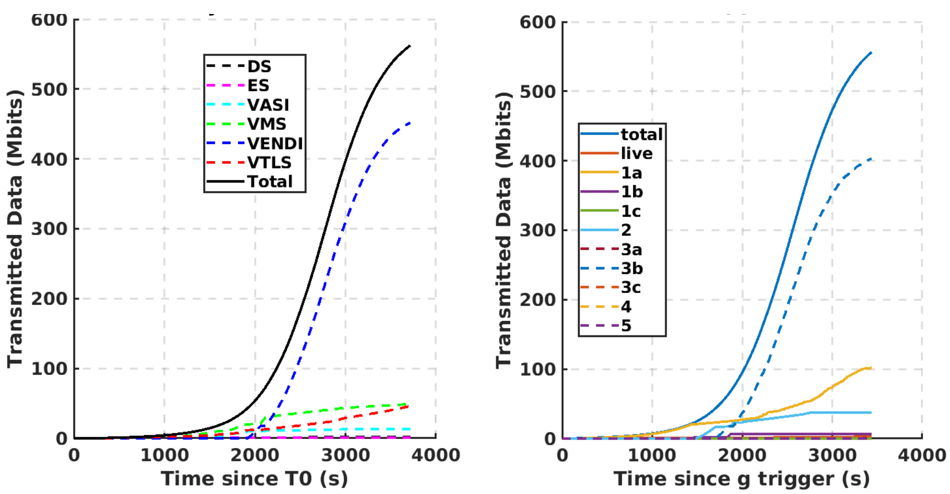


Fig. 16 Notional example of the DAVINCI data rate profile

bandwidth to transmit large amounts of data to the relay spacecraft.

For the EDL simulation, it is paramount to monitor the data for the various instruments and queues, while also modeling the prioritization model in the spacecraft flight software to understand the data flow. Eventually, the actual flight software that will be on the vehicles will be integrated in to the EDL simulation for software-in-the-loop testing, but at present, the prioritization algorithm under development has been implemented to provide mission designers feedback on how to further refine the algorithm and track the progress of various science objectives. Fig. 17 shows a single trajectory instance of the transmitted data classified by the instruments and by queues. The current model is described in Ref. [33].



(a) Data Transmitted by Instrument

(b) Data Transmitted by Queue

Fig. 17 Example of data rates for a single instance of the DAVINCI simulation.

Briefly, various first transmissions and re-transmissions of key scientific and engineering measurements are classified in queues. Then using a largely first-in-first-out (FIFO) structure, the flight software queues the data packets for transmission based on available data rate at that moment. The EDL simulation runs thousands of dispersed trajectories, and mission designers can then analyze statistics of data transmitted by queue, instrument, and time of transmission to compare against science objectives.

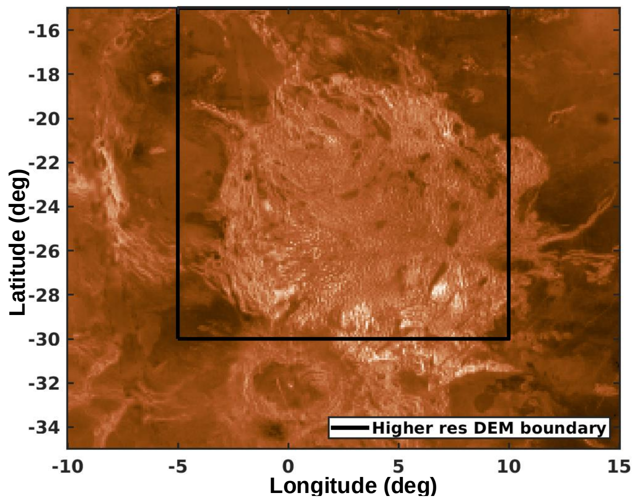


Fig. 18 Colorized Magellan SAR mosaic (image) of Alpha Regio with the bounds of the higher resolution DEM outlined in black

F. Terrain

The ground is modeled using a Digital Elevation Model (DEM). Using the POST2 ground routines described in [34], the simulation can determine the height above the planetary reference that the Zephyr will touchdown on. This is of particular importance for Alpha Regio as Alpha Regio is a local highlands. POST2 uses several layers for its ground calculations and enables the simulation to use a coarser ground routine for the overall planet while simultaneously using a finer ground model for areas of local interest.

The ground routine will search through the first ground layer for the elevation of the ground above the reference sphere. Then, using that height information as the initial guess for the ray tracing algorithm, the algorithm searches through the next ground layer. If data is found in the second ground layer, the simulation will use that data versus the data from the first layer. This enables the routine to handle overlapping ground data sets by defining prioritization. The ray tracing algorithm and the previous solution as the initial guess for future iterations which allows for quick turn-around times in development. The default ground layer is the planet reference ellipse, which will be used if no ground information was supplied. Details for this system can be found in Ref. [34].

The DAVINCI simulation uses a 1 degree per data point resolution built from Magellan data [35] for the first layer and a 900 m per data point DEM that spans from -5° to 10° longitude and -30° to -15° for Alpha Regio which uses observations from the Arecibo Observatory [36]. Fig. 18 shows a colorized image of the DEM, where lighter colors indicate a higher elevation and shows bounds of the higher resolution DEM.

G. Camera Modeling

The Zephyr science objectives include imaging the Venus surface during the descent sequence using VenDI, whose sapphire window can be seen in Fig. 3. The science requirement is to position the field of view of the different images taken in sequence be within the target ellipse and for sequential images to be overlapping. The goal from the overlapping images is so create multiple DEM's via structure-from-motino (SfM) in reconstruction [36].

In the DAVINCI EDL simulation, using constructs such as the POST2 antenna and field of view system, a body-fixed antenna pointing to the ground is defined. Ref. [37] describes how antennas and field of views (FOV) are defined in POST2. By defining the VenDI camera focal length, the center of the antenna boresight, and the field of view in terms of angles, the vertices of the rectangular field of view and ground relative pointing vectors can be constructed. The ray tracing algorithm from Ref. [34] is used to determine the intercept of the FOV vertices and their pointing vectors with the terrain model used within the simulation. The latitude and longitude of the intercepts can be defined for consecutive image series to see if the overlapping requirement is met. The simulation also produces an estimate for the Rayleigh scattering of the image expected due to the light traveling through the thick Venusian atmosphere based on the range of the intercept vector from VenDI to the ground.

Another capability provided in the simulation is to use a post-processing script to simulate the images taken by

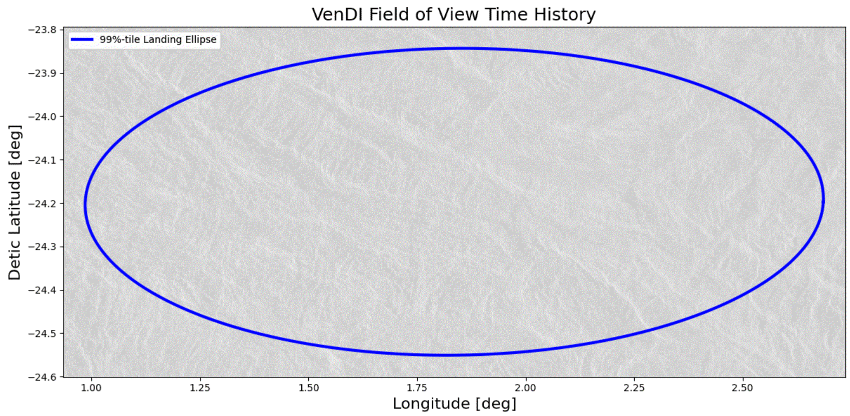


Fig. 19 Possible VenDI field-of-view during Venus descent over the Magellan SAR basemap.

individual trajectories from the simulation and superimpose them on the landing ellipse, creating a diorama of what VenDI will image during its descent. One can see the overlapping images during the different VenDI imaging sequences in Fig. 19, with subsequent image nested within the previous image similar to the science goals for creating DEMs.

Future development for the DAVINCI simulation will also use the capabilities described in Ref. [37] to parameterize the landing ellipse into a polynomial that can be convolved with the camera's field of view. This analysis can further provide metrics if the overlapping image sequence requirement is being met in Monte Carlo simulations, and could be used to target the vehicle trajectory to cover science areas of interest within the target landing ellipse.

H. Emulated Flight Software

The onboard flight computer for DAVINCI will use a predefined set of sequences, which command the onboard systems. These are split into two main categories: the CRIS sequences and the PFS sequences. The PFS sequences begin after separation from CRIS two days before entry interface. The POST2 simulation models the PFS descent sequences that occur after entry interface. These sequences begin by the g-trigger measurement. These descent sequences are then an open-loop controller with timestamps for the DAVINCI In-Situ Concept of Operations (DISCO). These are comprised of 3 components: the DS sequences which command things such as parachute deployment, the VenDI sequences which commands things such as when to take pictures, and the VMS/VTLS sequences, which provide commands such as ingesting the atmosphere for measurement.

These are integrated into the simulation by an emulated flight software model. The simulation triggers events in the initial entry phase using the PFS sequence, then starts the descent sequences using the g-trigger logic described above and finally starts a timer. These events are executed at specified timepoints. Science data is modeled by calculating the estimated data produced by the different instruments at these timepoints given by the data rate and data volume allocations that are specified by mission requirements. This information is then supplied to the data relay and data prioritization models described in earlier sections.

IV. Future Developments

The DAVINCI mission is still in early NASA Phase B of development, and still has several areas under development. Some of the forthcoming changes are described in this section.

A. Knowledge Error

Currently, the initial conditions for the CRIS and PFS are are provided by the Mission Design and Navigation (MDNAV) team at atmospheric interface minus 1 minute. These states are the delivery states from the MDNAV analysis and are used to initialize the true states of the CRIS and the PFS. Future work for the entry and descent modeling will entail ingesting the knowledge uncertainties as well from MDNAV analysis to better capture the comparison of true vehicle trajectory and navigation states of the vehicle. The team currently plans to use the construct described in

Ref. [38] to develop the true and navigated states from MDNAV's orbital determination solutions.

Simulating this difference in states will allow the simulation to better resolve errors in the pointing angle between the PFS and the CRIS caused by navigation errors between the predicted and actual location of PFS. The statistical differences can be quantified via Monte Carlo simulations. Capturing these nuances will help understand margins for the data relay and telecommunications analysis.

B. Rolling Moment Model for Zephyr

Characterizing the roll rate is an important need for the DAVINCI simulation as there are roll rate requirements imposed on the system by the science instruments. The current Zephyr aerodatabase does not provide a specified rolling moment coefficient or roll damping coefficient. From previous analysis of other missions such as Huygens [23] and Pioneer Venus [25, 39], it is expected that the roll rate will be a function of the spin vane incidence angle. Additional wind tunnel testing for the Zephyr shape is still needed to develop the coefficients of the model. The results of the simulation will be key to the choice of the spin vane incidence angle. It is expected that the roll rate model will be based on models discussed in Ref. [21].

C. Prototype Flight Software Integration

Another future development will be to integrate the prototype flight software into the entry and descent modeling. The emulated flight software is developed by the entry and descent modeling team for use in the EDL simulation. The prototype of the actual flight software is developed using NASA's core Flight Software (cFS) paradigm and will be used on the actual Zephyr to control triggering of events and science measurements [33]. The EDL simulation will integrate the cFS-based flight software to be able to run with the software-in-the-loop, increasing the fidelity of the analysis.

V. Conclusion

This work presents the updates to the model development for the DAVINCI mission. DAVINCI is the next NASA probe mission to Venus, and will be collecting various science measurements during its entry and descent. These events are modeled in an end-to-end simulation to provide predictions, and the simulation now incorporates flight specific aerodynamics, atmosphere, parachute, and data relay models to help designers understand the current performance. Future development, including integration of the flight software being developed for DAVINCI will provide added insight of vehicle performance at Venus.

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References

[1] National Academies of Sciences, E., and Medicine, *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032*, The National Academies Press, Washington, DC, 2023. https://doi.org/10.17226/26522, URL https://nap.nationalacademies.org/catalog/26522/origins-worlds-and-life-a-decadal-strategy-for-planetary-science.

[2] Garvin, J. B., Getty, S. A., Arney, G. N., Johnson, N. M., Kohler, E., Schwer, K. O., Sekerak, M., Bartels, A., Saylor, R. S., Elliott, V. E., Goodloe, C. S., Garrison, M. B., Cottini, V., Izenberg, N., Lorenz, R., Malespin, C. A., Ravine, M., Webster, C. R., Atkinson, D. H., Aslam, S., Atreya, S., Bos, B. J., Brinckerhoff, W. B., Campbell, B., Crisp, D., Filiberto, J. R., Forget, F., Gilmore, M., Gorius, N., Grinspoon, D., Hofmann, A. E., Kane, S. R., Kiefer, W., Lebonnois, S., Mahaffy, P. R., Pavlov, A., Trainer, M., Zahnle, K. J., and Zolotov, M., "Revealing the Mysteries of Venus: The DAVINCI Mission," *The Planetary Science Journal*, Vol. 3, No. 5, 2022, pp. 297–304. https://doi.org/10.3847/PSJ/ac63c2.

[3] Kornfeld, R. P., Prakash, R., Devereaux, A. S., Greco, M. E., Harmon, C. C., and Kipp, D. M., "Verification and Validation

of the Mars Science Laboratory/Curiosity Rover Entry, Descent, and Landing System," *Journal of Spacecraft and Rockets*, Vol. 51, No. 1251-1269, 2014, pp. 1–46. https://doi.org/10.2514/1.A32680.

[4] Striepe, S., Powell, R., Desai, P., Queen, E., Way, D., Prince, J., Cianciolo, A., Davis, J., Litton, D., Maddock, R., Shidner, J., Winski, R., O'Keefe, S., Bowes, A., Aguirre, J., Garrison, C., Hoffman, J., Olds, A., Dutta, S., Zumwalt, C., White, J., Brauer, G., Marsh, S., Lugo, R., Green, J., Williams, R., and Engel, M., *Program To Optimize Simulated Trajectories (POST II),* Version 4.3.0 r2321, 2020.

[5] Braun, R. D., Powell, R. W., Engelund, W. C., Gnoffo, P. A., Weilmuenster, K. J., and Mitcheltree, R. A., "Mars Pathfinder Six-Degree-of-Freedom Entry Analysis," *Journal of Spacecraft and Rockets*, Vol. 32, No. 6, 1995, pp. 993–1000. https://doi.org/10.2514/3.26720.

[6] Desai, P. N., Schoenenberger, M., and Cheatwood, F. M., "Mars Exploration Rover Six-Degree-of-Freedom Entry Trajectory Analysis," *Journal of Spacecraft and Rockets*, Vol. 43, No. 5, 2006, pp. 1019–1025. https://doi.org/10.2514/1.6008.

[7] Desai, P. N., Prince, J. L., Queen, E. M., Schoenenberger, M., Cruz, J. R., and Grover, M. R., "Entry, Descent, and Landing Performance of the Mars Phoenix Lander," *Journal of Spacecraft and Rockets*, Vol. 48, No. 5, 2011, pp. 798–808. https://doi.org/10.2514/1.48239.

[8] Way, D., Davis, J., and Shidner, J., "Assessment of the Mars Science Laboratory Entry, Descent, and Landing Simulation," AAS 13-420*, AAS/AIAA Space Flight Mechanics Conference,* Kauai, HI, 2013.

[9] Maddock, R., Cianciolo, A., Korzun, A., Litton, D., Zumwalt, C., and Karlgaard, C., "InSight Entry, Descent, and Landing Postflight Performance Assessment," *Journal of Spacecraft and Rockets*, Vol. 58, No. 5, 2021, pp. 1530–1537. https://doi.org/10.2514/1.A35023.

[10] Dutta, S., Way, D. W., Zumwalt, C. H., and Blette, D. J., "Postflight Assessment of Mars 2020 Entry, Descent, and Landing Simulation," *Journal of Spacecraft and Rockets*, Vol. 61, No. 3, 2024, pp. 847–857. https://doi.org/10.2514/1.A35771.

[11] Dutta, S., Guecha-Ahumada, N., Garrison, M., Hughes, K., and Johnson, M., "DAVINCI Venus Entry, Descent, and Landing Modeling and Simulation," *AIAA SCITECH 2023 Forum*, 2023, p. 1165.

[12] Kliore, A., Moroz, V., , and Keating, G., "The Venus International Reference Atmosphere," *Advances in Space Research*, Vol. 5, No. 11, 1985, pp. 1–304.

[13] Bougher, S., Hunten, D., , and Phillips, R., *Venus II - Geology, Geophysics, Atmosphere, and Solar Wind Environment*, University of Arizona Press, *Tucson, AZ*, 1997.

[14] Justh, H., Cianciolo, A. D., and Hoffman, J., "Venus Global Reference Atmospheric Model (Venus-GRAM): User Guide," Tech. rep., NASA/TM-20210022168, 2021.

[15] Lebonnois, S., Millour, E., Martinez, A., Pierron, T., Francois, F., Spiga, A., Chaufray, J.-Y., Montmessin, F., and Cipriani, F., "The Venus Climate Database," *European Planetary Science Congress. EPSC 2021*, 2021.

[16] Lorenz, R., "Touchdown on Venus: Analytic wind models and a heuristic approach to estimating landing dispersions," *Planetary and Space Science*, Vol. 108, 2015, pp. 66–72. https://doi.org/10.1016/j.pss.2015.01.003.

[17] Chadalavada, P., Andreini, M. J., Manwell, M. S., and Dutta, S., "DAVINCI Venus Atmospheric Model Comparisons," AIAA 2024-1913*, AIAA 2024 SciTech,* Orlando, FL, 2024.

[18] Lorenz, R., "Turbulence for extraterrestrial aviation: Gust specification for Dragonflyś powered flights," *Planetary and Space Science*, Vol. 214, 2022, pp. 1–8. https://doi.org/10.1016/j.pss.2022.105459.

[19] Mitcheltree, R. A., Moss, J. N., Cheatwood, F. M., Greene, F. A., and Braun, R. D., "Aerodynamics of the Mars Microprobe Entry Vehicles," *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, 1999, pp. 392–398. https://doi.org/10.2514/2.3458.

[20] Mitcheltree, R., Moss, J., Cheatwood, F., Green, F., and Braun, R., "Aerodynamics of the Mars Microprobe Entry Vehicles," AIAA 1997-3658, *22nd Atmospheric Flight Mechanics Conference,* New Orleans, LA, 1997.

[21] Dutta, S., Guecha-Ahumada, N. G., Andreini, M., Karlgaard, C., and Chan, M., "Results from the Helicopter Drop Test of the DAVINCI Descent Sphere," AIAA 2024-4328, *AIAA AVIATION,* Las Vegas, NV, 2024. https://doi.org/10.2514/6.2024-4328.

[22] Cruz, J., "Preliminary Aerodynamic Model for the VISAx Descent Probe," Tech. rep., NASA Langley Research Center, 2010.

[23] Lorenz, R., Lebreton, J.-P., Leroy, A., and Perez-Ayucar, M., "Evolution of the Huygens Probe Spin During Parachute Descent," *Journal of Spacecraft and Rockets*, Vol. 58, No. 3, 2021, pp. 609–618. https://doi.org/10.2514/1.A34818.

[24] Bienstock, B. J., "Pioneer Venus and Galileo Probe Heritage," ESA SP-544, *International Planetary Probe Workshop,* Lisbon, Portugal, 2003.

[25] "Pioneer Venus Program – Large & Small Probe Data Book," Contract NAS2-8300, HS507-5164, Hughes Aircraft Company, Space and Communications Group, June 1976.

[26] Desai, P., and Qualls, G., "Stardust Entry Reconstruction," *Journal of Spacecraft and Rocekts*, Vol. 47, No. 5, 2010, pp. 736–740. https://doi.org/https://doi.org/10.2514/1.37679.

[27] O'Farrell, C., and Clark, I. G., "Reconstructed Performance of Mars 2020 Parachute Decelerator System," *Journal of Spacecraft and Rockets*, Vol. 61, No. 5, 2024, pp. 1313–1328. https://doi.org/10.2514/1.A35976.

[28] Cruz, J. R., Way, D. W., Shidner, J. D., Davis, J., Adams, D. S., and Kipp, D., "Reconstruction of the Mars Science Laboratory Parachute Performance," *Journal of Spacecraft and Rockets*, Vol. 51, No. 4, 2014, pp. 1185–1196. https://doi.org/10.2514/1.A32816.

[29] Dutta, S., Karlgaard, C., Tynis, J., O'Farrell, C., Sonneveldt, B., Queen, E., Bowes, A., Leyleck, E., and Ivanov, M., "Advanced Supersonic Parachute Inflation Research Experiment Preflight Trajectory Modeling and Postflight Reconstruction," *Journal of Spacecraft and Rockets*, Vol. 57, No. 6, 2020, pp. 1387–1407. https://doi.org/10.2514/1.A34706.

[30] Abilleira, F., and Shidner, J., "Entry, Descent, and Landing Communications for the 2011 Mars Science Laboratory," *23rd International Symposium on Space Flight Dynamics,* Pasadena, CA, 2012. URL http://hdl.handle.net/2014/43032.

[31] Wallace, M., Litton, D., Martin-Mur, T., and Wagner, S., "Orbiters, CubeSats, and radio telescopes, oh my; entry, descent, and landing communications for the 2018 InSight Mars lander mission," *29th AAS/AIAA Space Flight Mechanics Meeting, Ka'anapali, HI*, 2019. URL http://hdl.handle.net/2014/49246.

[32] Sackier, C., et al., "Chapter VIII: Telecommunications Performance During Entry, Descent, and Landing of Mars 2020," *Mars 2020 Entry, Descent & Landing As-Flown Reconstruction Report*, Jet Propulsion Laboratory, 2021.

[33] Hageman, J., Pedraza, J. M., Garrison, M., Goodloe, C., and Dutta, S., "DAVINCI Descent Sphere Data Flow Design Overview and Initial Performance Estimates," *IEEE Aerospace Conference,* Big Sky, MT, 2025.

[34] Shidner, J., "An Efficient Ray-Tracing Method for Determining Terrain Intercepts in EDL Simulations," *IEEE Aerospace Conference,* Big Sky, MT, 2016. https://doi.org/10.1109/AERO.2016.7500591.

[35] Arvidson, R. E., Greeley, R., Malin, M. C., Saunders, R. S., Izenberg, N., Plaut, J. J., Stofan, E. R., and Shepard, M. K., "Surface modification of Venus as inferred from Magellan observations of plains," *Journal of Geophysical Research: Planets*, Vol. 97, No. E8, 1992, pp. 13303–13317.

[36] Garvin, J., Campbell, B., Arney, G., Getty, S., Gilmore, M., Pimentel, E., and Dotson, R., "Kilometer-Scale Topography of Alpha Regio, Venus with DAVINCI Mission Entry Corridor Science Implications," *Fall 2022 AGU,* Chicago, IL, 2022.

[37] Roelke, E., Green, J., Williams, R. A., Dutta, S., and Andreini, M., "Shape Approximation in Camera Fields of View for Parachute and Descent Imaging Visibility Applications," *2025 AIAA SciTech,* Orlando, FL, 2025.

[38] Gustafson, E. D., Halsell, C. A., Jefferson, D., Lau, E., Lee, J., McCandless, S. E., Mottinger, N., and Seubert, J., "Insight Orbit Determination," AAS 19-213*, AAS/AIAA Astrodynamics Specialist Conference,* Portland, ME, 2019.

[39] Lorenz, R., "Descent Dynamics of the Pioneer Venus Large Probe," AIAA 2022-2742, *26th AIAA Aerodynamic Decelerator Systems Technology Conference,* Toulouse, France, 2022.