DAVINCI Venus Entry, Descent, and Landing Modeling and Simulation

Soumyo Dutta*, Nelson G. Guecha-Ahumada†
NASA Langley Research Center, Hampton, VA 23681, USA

Matthew B. Garrison‡, Kyle M. Hughes§
NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

Mark Z. Johnson¶
Lockheed Martin Space, Littleton, CO 80120, USA

The Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission is scheduled to launch in June 2029 and explore Venus via two flybys and a probe descent scheduled for June 2031. The goals of the mission are to study the origin, evolution, and current state of Venus and to understand if it was habitable at a point in the past. The entry, descent, and landing (EDL) concept of operations of the probe leverages on the successful Pioneer Venus large probe mission. The science objectives of the mission levy certain requirements on the EDL system, such as landing in the scientifically important Alpha Regio Tessera and telemetering several gigabytes of instrumentation data to the orbiting relay spacecraft before the probe impacts the surface. In order to optimize the EDL sequence of the lander and to verify key driving requirements, a six degree of freedom EDL flight mechanics simulation has been created based on the best available aerodynamic and atmospheric models for Venus. This paper describes the EDL modeling and simulation and summarizes the current flight mechanics results for the mission.

I. Introduction

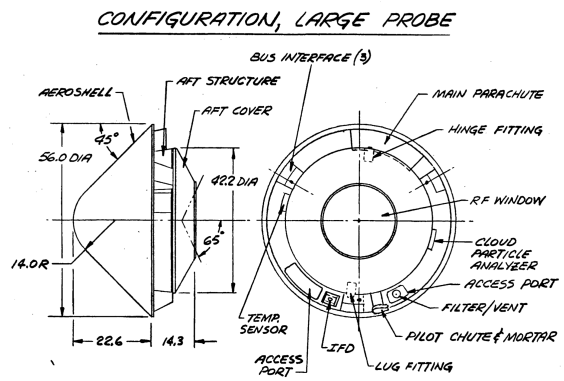
The Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission is scheduled to launch in June 2029 and explore Venus via two flybys and a probe descent currently scheduled for June 2031. DAVINCI is the 16th selection of the NASA Discovery Class program and its objectives include quantifying the chemical composition of the Venusian atmosphere, taking infrared descent imagery of the surface, and conducting remote observations of the dynamic atmosphere and cloud-deck. The goals are to study the origin, evolution, and current state of Venus, to understand if it was habitable at a point in the past, and to create an analog to hot terrestrial exoplanets similar to Venus [1].

The entry, descent, and landing (EDL) sequence used by the Probe Flight System (PFS) will be a crucial part of the mission, particularly in its delivery of the Descent Sphere (DS), which holds the majority of DAVINCI's on-board instruments for in-situ observations. The PFS will be released from the Carrier-Relay-Imaging Spacecraft (CRIS) two days before entry interface. The PFS will be spin-stabilized with a 5 rotations per minute (RPM) roll, will conduct a ballistic entry of the atmosphere, and will then traverse the Venus atmosphere in one hour. All essential on-board science and engineering data will be transmitted to the CRIS before reaching the Venusian surface. Landing is not part of the baseline mission; however, the DS may continue to transmit data after impact.

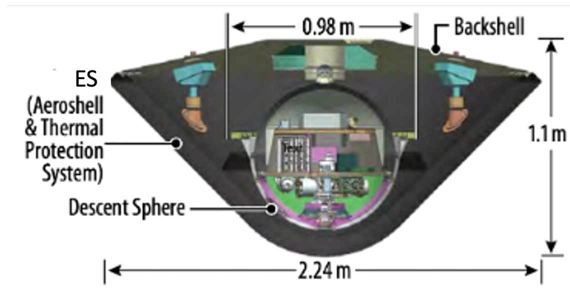
Although DAVINCI borrows its entry and descent design from the heritage of the successful 1978 Pioneer Venus large probe, DAVINCI's unique EDL requirements and advances in the EDL modeling and simulation of the last few decades have been reflected in an end-to-end flight mechanics tool that predicts performance. This paper will discuss DAVINCI's EDL sequence, the current EDL flight mechanics modeling effort, and show some preliminary metrics of flight performance.

---

*Aerospace Engineer, Atmospheric Flight and Entry Systems Branch, Senior AIAA Member.
†Aerospace Engineer, Atmospheric Flight and Entry Systems Branch, AIAA Member.
‡Aerospace Engineer, Instrument/Payloads Systems Engineering Branch.
§Aerospace Engineer, Navigation and Mission Design Branch.
¶Systems Engineer, Senior Staff, Deep Space Exploration.



(a) Pioneer Venus Large Probe (dimensions in inches) [2]

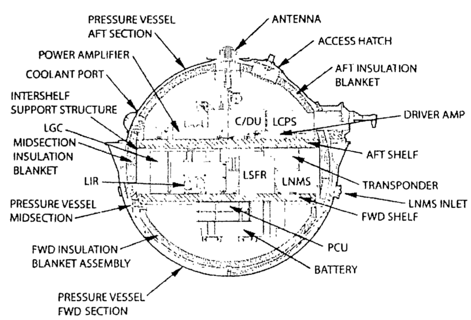


(b) DAVINCI PFS Configuration [1]

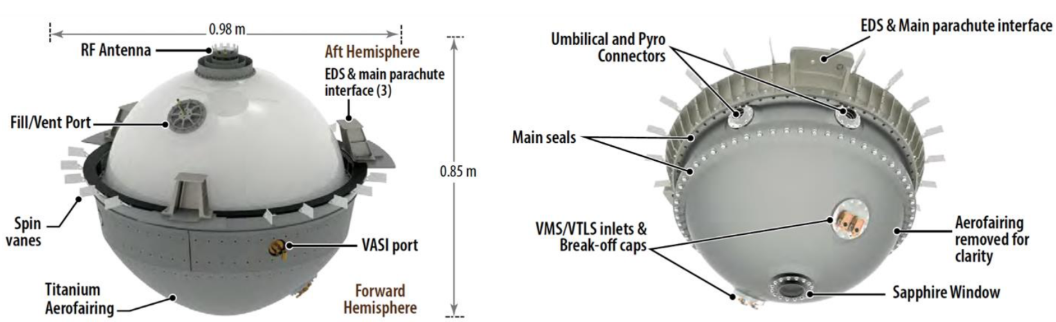
Fig. 1 Entry configurations for Venus probes.

II. DAVINCI Concept of Operations

DAVINCI borrows its entry vehicle configuration from Pioneer Venus (see Fig. 1(a)). The Entry System (ES) for DAVINCI is a 2.24 m diameter 45° sphere-cone with a relatively flat backshell profile (see Fig. 1(b)). The DS, which is the main scientific payload, is a spherical pressure vessel with spin vanes to achieve a desired rotation rate when it is freely descending in the Venusian atmosphere. Spin vane are fixed at angles with respect to the flow help the DS achieve the desired rotation rate [3]. The DAVINCI descent sphere (shown in Fig. 2(b)) with 0.87 m sphere diameter and 0.98 m drag plate to drag plate distance is similar in design to the Pioneer Venus large probe (shown in Fig. 2(a)) with a similar 0.98 m drag plate to drag plate diameter but a 0.78 m sphere diameter when comparing them by the outer mold line. The DAVINCI DS contains newer technologies and scientific instruments to study the deep atmosphere of Venus that is hard to observe remotely from orbiters.



(a) Pioneer Venus Large Probe Descent Sphere [4]



(b) DAVINCI Descent Sphere [1]

Fig. 2 Descent sphere configurations of Venus probes.

The deployment sequence for DAVINCI also relies on the heritage of the Pioneer Venus large probe, which is shown in Fig 3. A mortar deployed pilot parachute inflates and then pulls out the backshell and the main parachute. The descent sphere deployment begins with aeroshell separation followed by parachute jettison. Unlike Pioneer Venus, the DAVINCI project is currently not using conical ribbon parachutes. DAVINCI's pilot and main parachutes currently have disk-gap-band (DGB) canopies. DGB main parachutes have a long heritage from their use on all of the Mars missions and were selected due to their recent use on planetary missions, but further parachute design trades are planned. DAVINCI has a 1.8 m diameter pilot parachute, while its main parachute is 5.8 m in diameter. The EDL concept of operations, seen in Fig. 4, consists of a ballistic entry at an entry velocity of 10.4 km/s and -6.3° entry flight path angle, with the vehicle reaching peak deceleration of 32 Earth g's and peak convective heat flux of 500 W/cm^2.

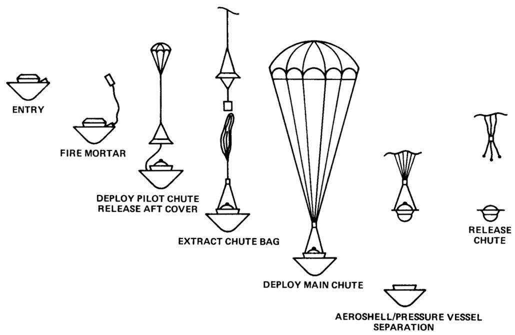


Fig. 3 Pioneer Venus Large Probe deployment sequence [4]. DAVINCI has a similar sequence.

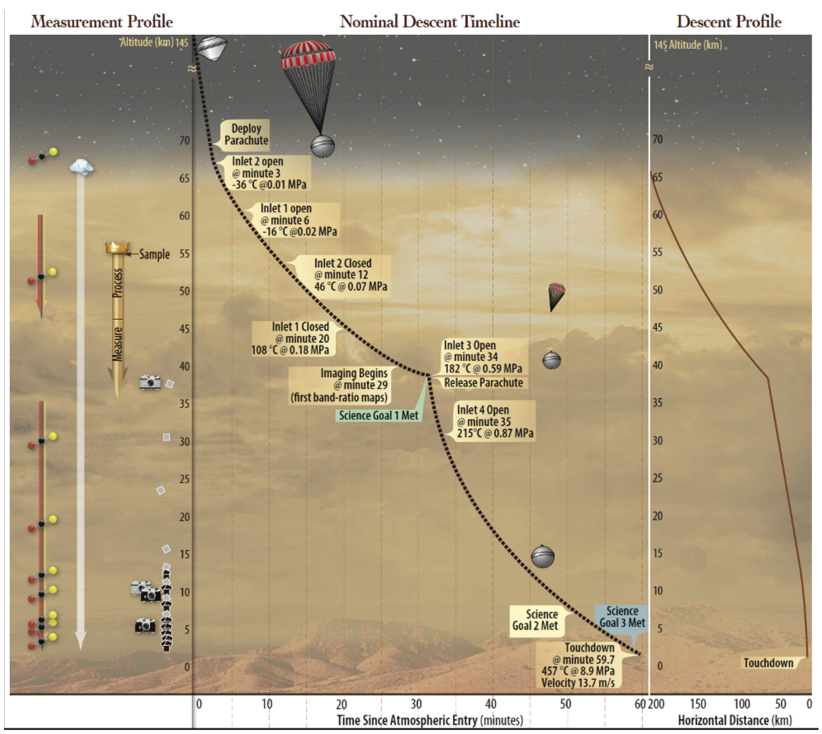


Fig. 4 DAVINCI EDL concept of operations [5].

The entry flight path angle for DAVINCI is much shallower than the -33.8° for Pioneer Venus, allowing the DAVINCI spacecraft to have lower peak accelerations and heat flux. Due to the thick Venusian atmosphere, as seen in a comparison with a typical Mars atmosphere in Fig. 5, the majority of the deceleration occurs in the altitudes between 80 and 100 km. Figure 6 shows a comparison of DAVINCI's trajectory with a typical Mars EDL trajectory, in this case Mars 2020 [6]. The atmospheric interface altitude considered by the DAVINCI project is 145 km and the atmosphere is currently simulated from that point down to the surface. However, future iterations of the simulation may extend the atmospheric initialization to higher altitudes. The large Mach dispersions at higher altitudes are rarefied flow for DAVINCI and are a reflection of the variability in atmospheric properties. The Venusian vehicle becomes subsonic at a very high altitude compared to Mars EDL. For DAVINCI, a subsonic DGB pilot parachute de-ploys at Mach 0.8 using a g-trigger and timer-based system similar to Pioneer Venus [2], and the pilot then pulls out the larger DGB main parachute shortly after reaching 70 km altitude. The DS traverses over the Alpha Regio Tessera for 30 mins on its main parachute before being released from the parachute and descending to the surface for another 30 mins. The long duration of flight in subsonic conditions allows the atmosphere to largely affect the trajectory of the spacecraft and creates modeling and simulation challenges.

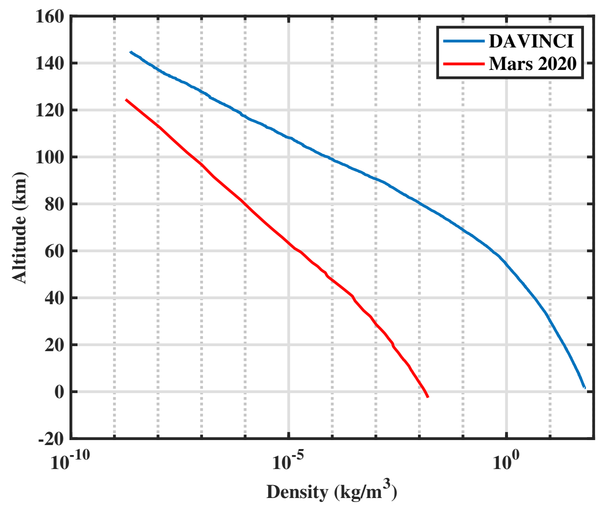
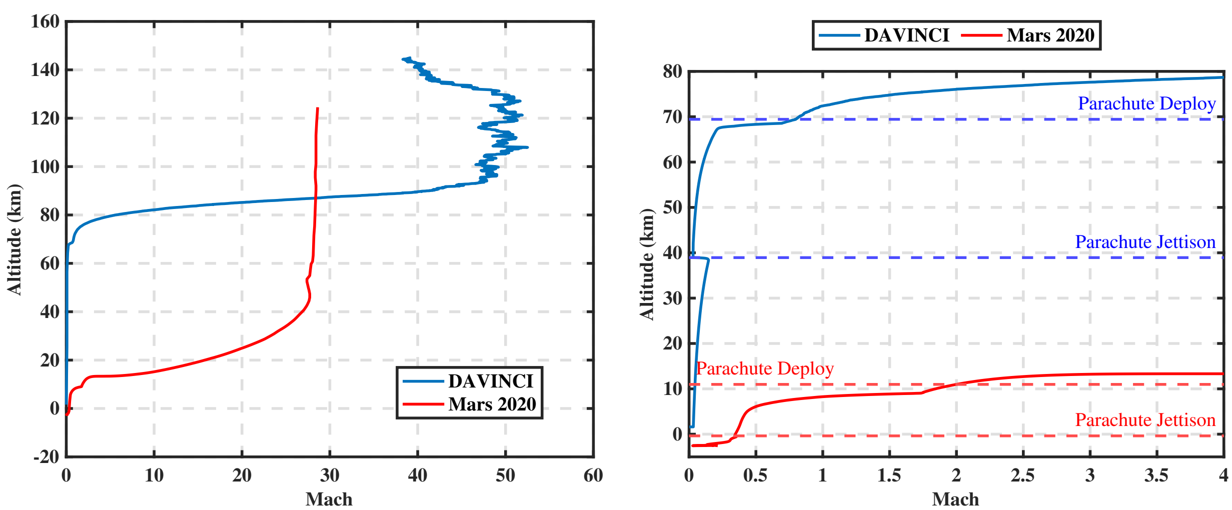


Fig. 5 Venus atmospheric density compared to Martian atmosphere.



(a) Altitude vs. Mach

(b) Zoomed-in View

Fig. 6 DAVINCI trajectory comparison against a typical Mars EDL trajectory from Mars 2020.

III. EDL Flight Mechanics Modeling

The Program to Optimize Simulated Trajectories II (POST2) is the tool used for end-to-end EDL simulations for the DAVINCI mission. POST2 is a six degree-of-freedom flight dynamics simulation tool that can simultaneously simulate the trajectory of up to 20 independent or connected rigid bodies. It is a generalized point mass, discrete-parameter targeting and optimization trajectory simulation program with multi-vehicle capabilities that integrates translational and rotational equations of motion along the trajectory. The simulation tool has significant EDL flight heritage as it has been used in the past successfully for several Mars EDL missions, such as Mars Pathfinder [7], Mars Exploration Rovers [8], Mars Phoenix [9], Mars Science Laboratory [10], Mars InSight [11], and Mars 2020 [6]. Although Mars and Venus have very different atmospheric densities (Fig. 5), both share very similar atmospheric composition and have largely CO_2 atmospheres, which allows many aerodynamic and entry models to be shared.

The DAVINCI simulation is a continuation of the POST2-based Mars end-to-end EDL simulations developed at the NASA Langley Research Center. The simulation starts at entry interface and models the trajectories of two independent bodies, CRIS and PFS. In future iterations of the simulation, both CRIS and PFS will have two variants based on the delivery states and the knowledge states. Jettisoned configurations, such as the pilot parachute and backshell, aeroshell, and the main parachute will be also modeled separately as independent vehicles in future versions of the flight mechanics simulation. Interaction between interconnected bodies, such as the parachute and the aeroshell, are modeled using multi-body force models originally developed for the Mars Exploration Rovers' simulations [8, 10].

The end-to-end simulation, which incorporates vehicle, planet, and atmospheric models, is used during mission planning to assess the system's performance against requirements and response to off-nominal conditions. In order to quantify the robustness of the system, Monte Carlo analysis is conducted using the simulation. A preselected group of input variables are stochastically dispersed and statistics on metrics of interest are tracked at specific EDL events. The output metrics are collected for multiple runs of the simulation. The following sections will summarize the state of some of the key EDL models.

A. Atmosphere

Atmospheric data for Venus is sparse – hence the impetus of the mission – and utilizing various models and scenarios from the past flight data is essential to predicting DAVINCI's flight performance. Currently, the atmospheric model in the simulation is the Venus Global Reference Atmospheric Model (GRAM), which is based on the Venus International Reference Atmosphere (VIRA) and derived from Pioneer Venus orbiter and probe data as well as Venera probe data [12].

GRAM atmospheric data is useful for engineering-level analysis, but it is based on global atmospheric predictions and is predicated on a sparse dataset, so it may not provide the most accurate estimate of conditions at Alpha Regio Tessera. EDL performance parameters, such as landing footprint, are sensitive to the winds used in the simulation. To improve the fidelity over global models, an engineering wind model based on Pioneer Venus probe data was developed for DAVINCI [13]. The model reflects the consequence of the super-rotating atmosphere of Venus, which cause large zonal (East-West) winds and smaller meridional (North-South) winds.

The atmospheric properties also affect the link relay budget due to the signal attenuation expected by the thick Venusian atmosphere. Currently, the project is using empirically derived attenuation models such as the one in Ref. [14]. However, the DAVINCI project is assembling a Council of Atmosphere consisting of atmospheric scientists and engineers, similar to Mars EDL missions, to characterize flight-relevant atmospheric properties. The updated reference atmosphere will be reflected in a future iteration of the EDL simulation.

B. Aerodynamics

Although DAVINCI relied on Pioneer Venus heritage for various EDL vehicle configurations, the state-of-the-art of aerodynamic modeling has improved since the late 1970's. Thus, despite the existence of historical modeling data for the various configurations of DAVINCI at Venus and other planetary bodies, the aerodynamics models for the entry capsule, DGB parachute, and DS are being reanalyzed to understand the applicability for the 2031 mission.

For example, aerodatabases exist for 45° sphere-cone entry body from Pioneer Venus [15] and Mars Microprobe [16]. However, the backshell of DAVINCI vehicle is less convex than either Pioneer Venus or Mars Microprobe, and will affect the dynamics of the vehicle in transonic flight. Hence, additional analysis will be needed for the entry body despite the existence of high-quality historic data. Currently, the simulation uses the Mars Microprobe aerodynamics, which is based of Pioneer Venus data but also includes more recent computational fluid dynamics (CFD) and wind tunnel data, but in future iterations, a DAVINCI specific aerodatabase will be created to account for the variation in the vehicle shape, planetary environments, and improvement in CFD tools.

The DAVINCI parachutes are DGBs, which allows leveraging of historical data for parachute modeling. Currently, the parachute aerodynamic model is based on wind tunnel test and flight data from Mars Science Laboratory [17–19]. Changes to account for atmospheric differences between Venus and Mars, and their effect on parachute fabric porosity and other parachute strength related parameters are planned. Additionally, for DAVINCI, the parachute will traverse through sulfuric acid clouds at 40-60 km altitude region, and the effect of the caustic chemical on parachute strength properties will be addressed through testing and updated modeling inputs that are very specific for DAVINCI.

For the descent sphere, the aerodynamics are currently based on a mixture of CFD and Pioneer Venus reconstructed data [20]. However, the aerodynamics of descent sphere are a function of the outer mold line (OML), spin vanes, and drag plate design. For example, past descent spheres like the Huygens, have shown large deviations from predicted aerodynamics due to small differences in the OML, such as unaccounted appendages that were in the flow [3]. Future iterations of the DAVINCI simulation will involve a DS specific aerodynamics model based on further reconstruction of the Pioneer Venus large probe data [21] and wind tunnel and drop tests conducted on the DAVINCI OML.

IV. Challenges and Analysis

The key scientific instruments are in the DS and will start taking measurements once the DS is exposed to the Venus atmosphere after main parachute deployment. The instruments include the Venus Mass Spectrometer (VMS), Venus Tunable Laser Spectrometer (VTLS), Venus Atmospheric Structure Investigation (VASI), and Venus Descent Imager (VenDI). The DS will also include a student collaboration experiment named Venus Oxygen DS Fugacity (VfOx) which will measure oxygen composition [1].

The experiments on-board are expected to generate several gigabytes of data which must be transmitted to the CRIS before surface impact, after which the spacecraft is not required to function [5]. Likewise, the scientific instruments must operate within specific environmental envelopes – minimum and maximum altitude, descent rate, rotation rates – to attain their study objectives.

Due to the constraints levied by the science objectives and the open-loop command and control architecture of the vehicle, the EDL flight mechanics simulation must accurately account for atmospheric and aerodynamic modeling of the ES, parachute, and DS as well as model the communication between the DS and CRIS. Predictions from the flight mechanics tool are used to set parameters of the spacecraft sequences which are used to trigger various configuration changes and the science data relay, including an innovative adaptive data rate (ADR) between the DS and the CRIS. The following sections considers some of these challenges and the current state of the analyses.

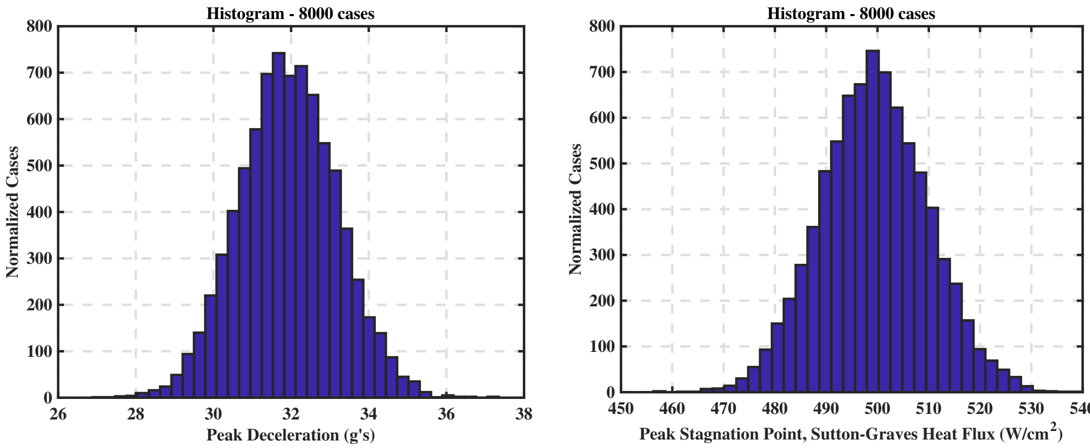
A. Entry Environment

Figure 7 shows the peak acceleration and stagnation point heat flux using the Sutton-Graves indicator for the current DAVINCI design. Due to the relatively shallow flight path angle of DAVINCI compared to past Venus entries, such as the VEGA and Pioneer Venus probes [22], the peak acceleration is an order of magnitude lower than past missions which had greater than 200 g's at peak acceleration. The peak convective heat flux is reasonable for traditional ablative thermal protection system material, which currently is Advanced Carbon-Carbon (ACC) and was the thermal protection system (TPS) for the Genesis spacecraft [23]. On Venus radiative heating is also very important and applicable radiative and total heat flux indicators will be captured in a future iteration of the simulation. Currently, the trajectory inputs from the simulation are used to do aerothermal calculations in a separate tool.

Unlike Mars missions, the entry portion of DAVINCI is very short in time with subsonic, parachute deployment occurring within the first 5% of the total EDL timeline. However, the vehicle undergoes a large deceleration in a very short time (3 minutes) and traverses potential zones of vehicle instability for blunt, entry bodies, especially in the transonic regime. The vehicle attitude at parachute deployment is a key metric of interest, with a small angle desired to avoid parachute deployment in a non-axial direction from the vehicle which could induce undesired capsule dynamics. Figure 8 shows that the current expected dispersion in total angle of attack at pilot deploy is small; however, currently the simulation uses the Mars Microprobe aerodatabase, which was designed for different trajectory conditions and has a hemispherical aftbody that is different from DAVINCI's flatter aftbody. Dynamic stability in the transonic regime is greatly affected by aftbody geometry [24] and as future iterations of the DAVINCI aerodatabase are developed, the total angle of attack metric will be closely monitored.

B. Flight Sequence Timing

DAVINCI relies on open-loop controls and timers for command and control of the spacecraft and science data acquisition. The flight mechanics simulation is critical to estimate event timing and to verify that the mission and science requirements are being met. For example, one science requirement specifies that the VMS must make measurements every 1 km below the 40 km altitude above mean planet radius. The timing of the VMS sampling is informed by the



(a) Peak deceleration (b) Peak heat flux

Fig. 7 DAVINCI flight performance during the entry phase.

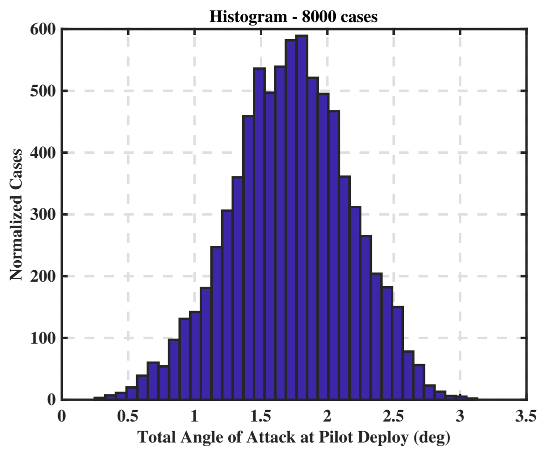


Fig. 8 Total angle of attack at pilot parachute deployment (Mach 0.8).

vertical speed at the start of the sample period, which is shown in Fig. 9. Based on the fastest vertical speed at this time, approximately 46 m/s, samples should be taken every 20 s. Similar science acquisition timings are based on other performance statistics from the flight mechanics simulation.

A challenge in determining the proper timing sequence is due to the non-uniform terrain in the Alpha Regio Tessera. Although Venus is a very spherical planet, the terrain at the targeted science region is very mountainous, creating a large variation in the surface altitude with respect to the mean radius of the planet (Fig. 10). The terrain in the simulation is based on a sub-kilometer resolution digital elevation map (DEM) created by the DAVINCI science team based on the Magellan orbiter imaging and Earth-based observations from the Arecibo observatory [25]. The variation in the surface height across the DAVINCI trajectories causes variation in timing of events that are based on height above ground level. For example, if a specific instrument measurement is to commence at 5 km above ground level (AGL), the time of that event is variable as seen in Fig. 10 and must be accounted in the timers set for the sequence.

C. Landing Location

The current landing footprint for DAVINCI is located within the Alpha Regio Tessera, as seen in Fig. 11. The 99%-tile confidence interval ellipse is 313 by 112 km and is elongated in the longitudinal direction due the wind that causes the spacecraft to drift in the zonal direction during parachute flight and terminal descent. The ellipse is currently in the region that satisfies science requirements for tessera imaging, but it is expected that ellipse placement could be

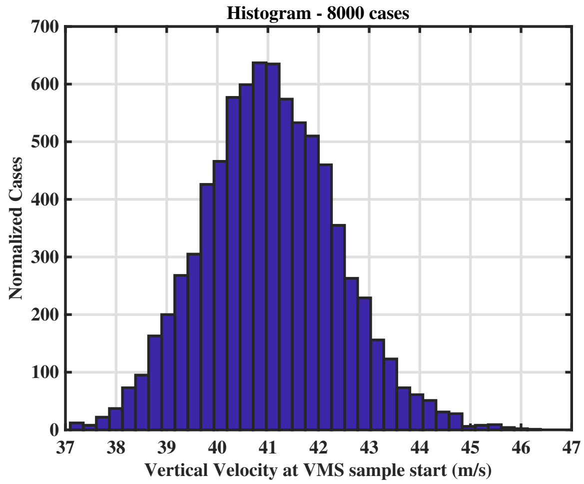
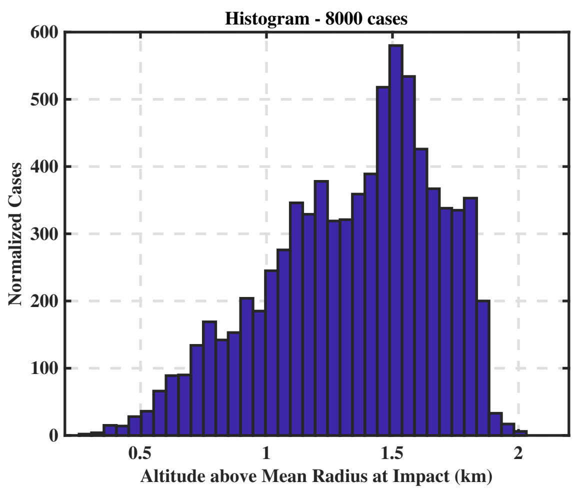
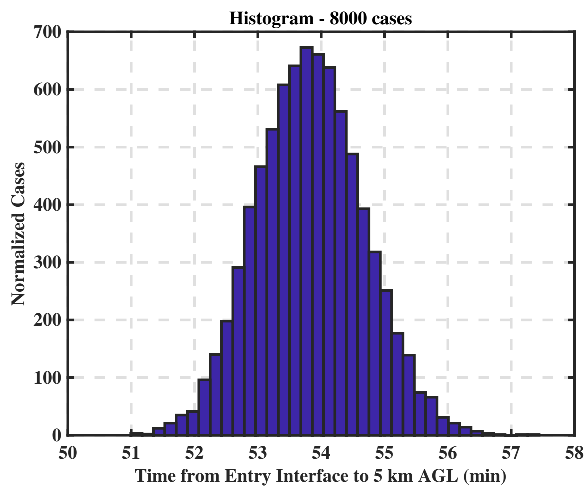


Fig. 9 Vertical velocity at start of VMS sample, used to determine VMS sampling frequency.



(a) Surface Altitude Variation

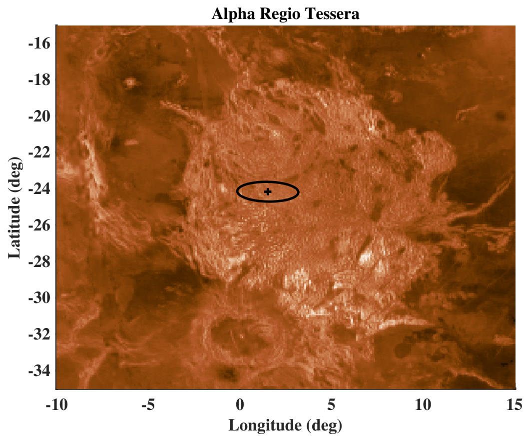


(b) Time Variation at 5 km AGL

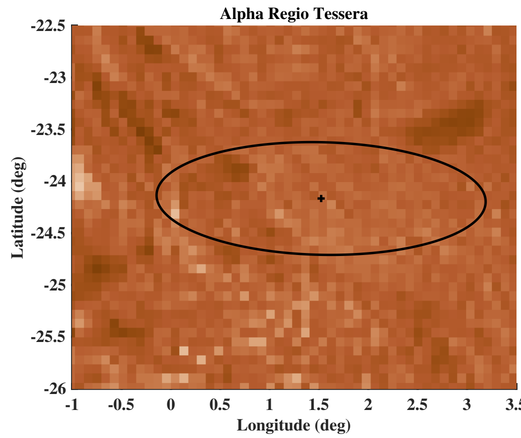
Fig. 10 Variation of the surface altitude with respect to the mean radius and timing of altitude based events for DAVINCI.

optimized in future design cycles as models mature.

The current EDL modeling consists of broadly four major dispersions – delivery errors, aerodynamic modeling uncertainties, atmospheric uncertainties, and mass dispersions. When the contribution of each of these models are considered as part of the overall landing ellipse dimensions, major and minor axes, as seen in Fig. 12, atmospheric dispersions are the largest contributors. The percentage contributions are computed by turning on only one model dispersions at a time in the Monte Carlos and then aggregating the results to understand the relative contribution of each model, similar to the work done in Ref. [26]. Unsurprisingly, when the spacecraft is at the atmospheric interface (or entry), all of the vehicle dispersions in the major and minor axes are due to delivery error from the interplanetary navigation. However, as the vehicle traverses the atmosphere, atmospheric uncertainties play a larger role in the trajectory dispersions. Aerodynamic dispersions, especially parachute and descent sphere aerodynamics, result in the next largest contribution in the major axis of trajectory dispersions, while mass dispersions are insignificant in their contributions to trajectory dispersion. Since the ellipse sizes are the largest in the major axis direction, improved atmospheric and aerodynamic models may reduce the landing ellipse size at the surface, which in turn has ramifications for the entry vehicle pointing back to the CRIS.

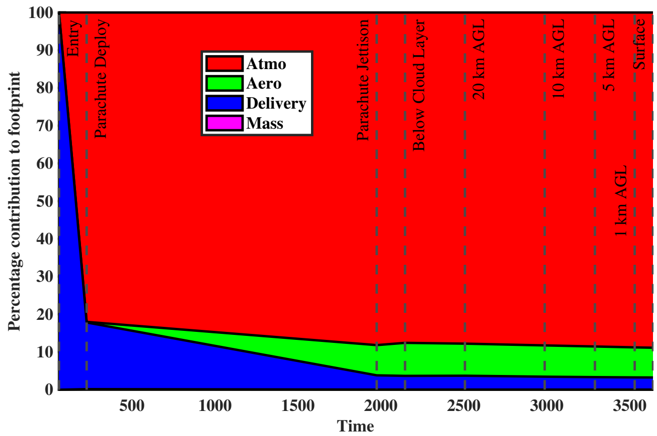


(a) Ellipse within the Alpha Regio Tessera

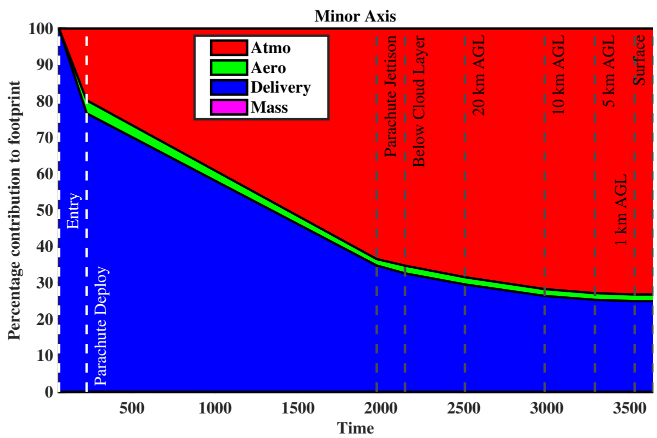


(b) Zoomed-in View

Fig. 11 DAVINCI landing footprint at 99% confidence interval.



(a) Major Axis

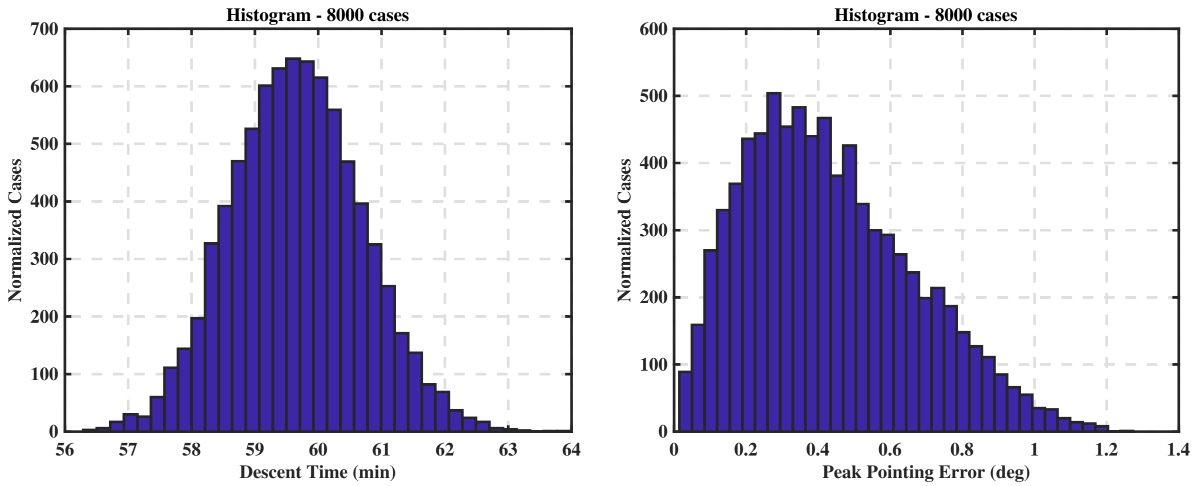


(b) Minor Axis

Fig. 12 Percentage contribution of various EDL models to size of the footprint at various events.

D. Pointing Accuracy and Telecommunications

One of the primary requirements for the EDL system is to transmit the scientific data on board the DS to the relay satellite CRIS before it reaches the surface, since the spacecraft is not required to survive impact. The total descent time from atmospheric interface and the maximum pointing angle between the PFS or DS and CRIS are shown in Fig. 13. Current performance estimates show that the vehicle has approximately one hour to upload the data and the current worst pointing angle between the DS and CRIS is acceptably small. As the vehicle design matures, the descent time and pointing angle metrics will be monitored to maintain performance within acceptable means.



(a) Time from atmospheric interface to impact (b) Maximum pointing angle between probe and CRIS

Fig. 13 DAVINCI flight performance near the surface.

The simulation also models the adaptive data rate (ADR) of the link budget between the PFS and CRIS. The link budget is based on usual telecommunication equations that have been used in the POST2 simulation for previous missions [27–29]. However, specific some DAVINCI specific updates include Venus-specific atmospheric attenuation models and the step-wise increases in data rates to meet signal-to-noise ratio thresholds.

The potential data rates based on a minimum margin and requirement margin thresholds are shown in Fig 14. Note, TZERO is the start of a timer for the PFS that begins 60 s prior to entry interface. On the day of flight, the actual data rate can be higher than either of these predictions, but for current engineering requirements, these data rates are used to maintain healthy link margins. The step increases in the data rates are an example of the rate changing due to variations in some link budget metrics, like the range between PFS and CRIS, the atmospheric attenuation, and maintenance of specific signal-to-noise thresholds for specific time periods. One of the challenges for the DAVINCI mission is that the current design results in decreasing data rates when the largest data products by volume are created between 5 km AGL and the surface. Although the current design meets minimum science objectives, design changes to the trajectories of the PFS and CRIS are being analyzed to optimize data rates in the crucial science phase.

In future iterations of the simulation, the data creation models for the various on-board instrumentation and an uplink data prioritization scheme will be included within the simulation to provide an estimate of data created, queued, and uplinked. Statistics on items such as which specific data packets could be uplinked in 99% of cases will provide designers flexibility in tuning the flight sequencing and data prioritization to optimize the science return.

E. Requirement Met or Violated Tracking

The EDL simulation already computes many metrics that are used for requirement evaluation from the Mission Requirements Document (MRD). Hence, a module was developed to evaluate all current MRD items for every case of a Monte Carlo simulation. Summaries of how many requirements were met, violated, or came within a pre-determined warning zone are provided at the completion of the Monte Carlo. Future iterations of the simulation will keep the metrics up to date with the MRD and the module will allow engineers the capability to do regression testing of current set of requirements while identifying potential trades that could lead to violations.

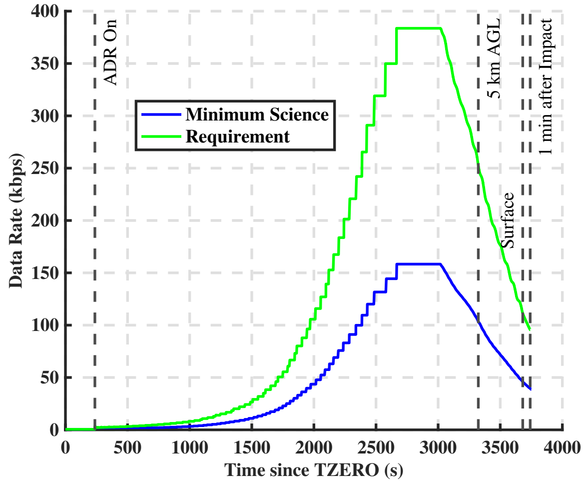


Fig. 14 Data rate predictions for DAVINCI based on the Adaptive Data Rate model.

V. Conclusion

The 2031 DAVINCI mission will be the first US spacecraft since the Pioneer Venus multiprobes in 1978 to enter the Venus atmosphere. The EDL sequence of DAVINCI is based on the Pioneer Venus large probe mission, but the scientific instruments have been developed to understand the origin, evolution, and current state of the planet and to decipher if it was habitable in the past. A six degree of freedom EDL flight mechanics simulation has been developed to understand system performances. Current best estimates of aerodynamics and atmospheric models based on historical data are used in the flight mechanics simulation, but these models will be improved in the future based on experimental data or reanalysis of past flight data. Based on current modeling and simulation, the DAVINCI vehicle is shown to successfully target the desired Alpha Regio Tessera and that metrics of interest are within the acceptable tolerances.

Acknowledgments

The authors would like to thank present and past members of the DAVINCI team who provided feedback that led to the development of the current flight mechanics simulation. The authors would like to thank Ralph Lorenz, David Way, and Colby Goodloe for their insight about the DAVINCI EDL. The authors would also like to thank Jim Garvin, Stephanie Getty, and Giada Arney for providing information about the science behind the mission.

References

[1] 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.

[2] Talley, R., "Pioneer Venus Deceleration Module Final Report," Tech. rep., General Electric, Re-entry & Environmental Systems Division, Philadelphia, PA, 1978.

[3] 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.

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

[5] Sekerak, M., Saylor, R., Goodloe, C., Bartels, A., Tompkins, S., Amato, M., Everett, D., Hur-Diaz, S., Hughes, K., Garrison, M., Sayal, C., Getty, S., Arney, G., Johnson, N., Garvin, J., Wade, D., Sutter, B., Cuddy, C., Linn, T., and McGee, M., "The Deep Atmosphere Venus Investigation of Noble gases, Chemistry and Imaging (DAVINCI) Mission: Flight System Design Technical Overview," *IEEE Aerospace Conference,* Big Sky, MT, 2022.

[6] Way, D., Dutta, S., Zumwalt, C., and Blette, D., "Assessment of the Mars 2020 Entry, Descent, and Landing Simulation," AIAA 2022-0421*, AIAA SciTech 2022, AIAA Atmospheric Flight Mechanics Conference,* San Diego, CA, 2022.

[7] 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.

[8] 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.

[9] 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.

[10] 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.

[11] 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.

[12] Justh, H., Justus, C., and Keller, V., "Global Reference Atmospheric Models, including Thermospheres, for Mars, Venus and Earth," AIAA 2006-6394*, AIAA/AAS Astrodynamics Specialist Conference and Exhibit,* Keystone, CO, 2006.

[13] 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.

[14] Du Toit, C., Everett, D., and Lorenz, R., "Modeling of Venus Atmospheric RF Attenuation for Communication Link Purposes," *2019 IEEE Aerospace Conference,* Big Sky, MT, 2019, pp. 1–20. https://doi.org/10.1109/AERO.2019.8741928.

[15] McCloy, R., "Entry Dynamics Performance Predictions for Pioneer Venus Probes," AIAA 1978-1370, *4th Atmospheric Flight Mechanics Conference,* Palo Alton, CA, 1978.

[16] 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.

[17] Cruz, J., Way, D., Shidner, J., Davis, J., Powell, R., Kipp, D., Adams, D., Sengupta, A., Witkowski, A., and Kandis, M., "Parachute Models Used in the Mars Science Laboratory Entry, Descent, and Landing Simulation," AIAA 2013-1276, *AIAA Aerodynamic Decelerator Systems (ADS) Conference,* Daytona Beach, FL, 2013.

[18] 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.

[19] Zumwalt, C., Cruz, J., O'Farrel, C., and Keller, D., "Wind Tunnel Test of Subscale Ringsail and Disk-Gap-Band Parachutes," AIAA Paper No. 2016-3882*, AIAA Aviation Conference 2016,* Washington, DC, 2016.

[20] Blanchard, R., Phillips, W., Kelly, G., and Findlay, J., "Venusian Probes Subsonic Drag Determination from Flight Data," *Journal of Spacecraft*, Vol. 19, No. 2, 1982, pp. 139–144. https://doi.org/10.2514/3.62223.

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

[22] Dutta, S., Smith, B., Prabhu, D., and Venkatapathy, E., "Mission Sizing and Trade Studies for Low Ballistic Coefficient Entry Systems to Venus," *IEEE Aerospace Conference,* Big Sky, MT, 2012. https://doi.org/10.1109/AERO.2012.6187002.

[23] Venkatapathy, E., Gasch, M., Stackpoole, M., Muppidi, S., and Morgan, J., "Robust and Mass Efficient Thermal Protection Systems for Future Venus Missions," *19th Meeting of the Venus Exploration Analysis Group (VEXAG),* Laurel, MD, 2021. URL https://www.hou.usra.edu/meetings/vexag2021/eposter/8037.pdf.

[24] Kazemba, C., Braun, R., Clark, I., and Schoenenberger, M., "Survey of Blunt-Body Supersonic Dynamic Stability," *Journal of Spacecraft and Rockets*, Vol. 54, No. 1, 2017, pp. 109–127. https://doi.org/10.2514/1.A33552.

[25] 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.

[26] Dutta, S., and Way, D., "Comparison of the Effects of Velocity and Range Triggers on Trajectory Dispersions for the Mars 2020 Mission," AIAA 2017-0245, *AIAA Atmospheric Flight Mechanics Conference,* Grapevine, TX, 2017.

[27] 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.

[28] 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.

[29] 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.