

Flyby Trajectory Analysis and Thermal Simulation of a Venus Atmospheric Probe



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Space Systems Design Laboratory (SSDL)
Guggenheim School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA, 30332

Author:
Roshan Selvaratnam

Academic Advisor:
Dr. E. Glenn Lightsey

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Roshan Selvaratnam*

Georgia Institute of Technology, Atlanta, GA, United States

E. Glenn Lightsey†

Georgia Institute of Technology, Atlanta, GA, United States

Cupid's Arrow is a proposed interplanetary Venus mission aimed at sampling the noble gases in its atmosphere. These inert elements can provide an insight into the history of the planet's formation and provide a reference for comparison with the Earth. The mission is comprised of a mothership and an atmospheric sample collection probe. This study is focused on the latter which will be deployed into Venus' atmosphere and descend to an altitude of 120 km. The thermal environment of the Venusian exosphere is the primary driver of the probe design both in terms of its structure and material composition. The mission architecture being considered for this study takes advantage of a gravity assist flyby trajectory. The probe will be dropped off as a secondary payload en route to the spacecraft's primary destination. The entry conditions at Venus and the trajectory of the probe relative to the mothership were determined using 2-body orbital mechanics. Using planar equations of motion, the probe's entry into Venus' atmosphere was simulated to predict the thermal environment that it would encounter. Initial results show a peak heat rate of approximately 220.3297 W/cm², a peak deceleration of 2.7654 Earth g's and a total heat load of 15535 J/cm². The results of the thermal environment model and relative trajectory analysis were used to validate the baseline communications and TPS design. In addition to Venus, this mission concept could be used to explore other planetary atmospheres, especially those frequented by interplanetary flybys.

NOMENCLATURE

TPS	= Thermal Protection System
PICA	= Phenolic Impregnated Carbon Ablator
POST2	= Program to Optimize Simulated Trajectories II
CFD	= Computational fluid dynamics
r_v	= Radius of Venus
V	= Velocity of probe
h	= Altitude
γ	= Flight path angle
β	= Ballistic coefficient
L/D	= Lift-to-drag ratio
ρ_0	= Reference density
q	= Stagnation point convective heat rate

* Graduate Student, Space Systems Design Lab (SSDL), Guggenheim School of Aerospace Engineering

† Professor, Director of Space Systems Design Lab (SSDL), Guggenheim School of Aerospace Engineering

r_n	= Effective nose radius
k	= Sutton-Graves constant
R_p	= Radius of the planet
H	= Scale height
V_∞	= Hyperbolic excess velocity
V_{arr}	= Spacecraft heliocentric arrival velocity
V_p	= Heliocentric velocity of planet
R_{SOI}	= Radius of the sphere of influence

INTRODUCTION

During the advent of space exploration, Venus, also known as the Earth's twin, was by far the most popular destination. In total, 23 spacecrafts have at least partially completed a mission to Venus, most of which occurred between 1961 and 1984. Since then, the international space community have gradually shifted their focus towards Mars and the outer planets in the solar system. In fact, the United States' last dedicated mission to Venus (Magellan) was launched way back in the 1989. Having said that, several space agencies have expressed a renewed interest in a Venus mission. The Venus Exploration Analysis Group (VEXAG) at NASA is interested in the formation and evolution of the Venusian atmosphere. Cupid's Arrow is a proposed mission to study the atmospheric content of Venus, in particular the abundance of certain noble gases (Ne, Ar, Kr, Xe) and their isotopic ratios in the homopause [1]. These inert elements can provide a history into the planet's formation and provide a reference for comparison with the Earth.

The mission is comprised of a mothership and an atmospheric sample collection probe. This study is focused on the latter which will be deployed into Venus' atmosphere and descend to an altitude of 120 km [2]. The mission architecture being considered for this study takes advantage of a gravity assist flyby trajectory. The probe will be dropped off as a secondary payload en route to the spacecraft's primary destination. This approach not only circumvents the need for a dedicated mission to Venus but also provides an additional science return for a fraction of the cost. The allure of this mission concept also extends beyond Venus as it can be used to explore other planetary atmospheres

The relative trajectory between the probe and the mothership as well as the former's entry conditions at Venus were determined using simple 2-body orbital mechanics. The relative range and velocity between the two were used to determine the time available for communication (i.e., scientific data from payload) between the two spacecraft before they're out of range. Using planar equations of motion, the probe's entry into Venus' atmosphere was simulated to predict the thermal environment that it would encounter. The thermal environment of the Venusian exosphere is the primary driver of the probe design both in terms of its structure and material composition.

The expected outcome of this research includes: 1) The relative trajectory of the atmospheric probe with respect to the mothership 2) The expected approximate thermal environment of the Venusian atmosphere during the probe encounter.

METHOD

Probe and Mothership Relative Trajectory

The relative trajectory between the probe and the mothership especially during the former's encounter with the Venusian atmosphere is crucial from a communications standpoint. The probe must transmit the data collected by the spectrometer to the mothership before the two spacecraft are out of communication range. The relative motion between the probe and the mothership – for our purposes – was simulated as planar two-body motion (see Eq. 1). In addition, the analysis was focused on the portion of the overall trajectory that lied within the sphere of influence of Venus, only taking into account its gravitational acceleration (patched conic approximation).

$$\ddot{\vec{r}} = -\frac{\mu}{r^3}\vec{r} \quad (1)$$

$$\vec{V}_{\infty/Venus} = \vec{V}_{arr} - \vec{V}_p \quad (2)$$

The initial conditions for the orbit propagator were the boundary conditions (R_{SOI} and V_{∞}) at the edge of the sphere of influence. Assuming a Hohmann trajectory, the arrival velocity of the spacecraft – prior to separation – at Venus was determined. The hyperbolic excess velocity was then calculated using Eq. 2. The radius of the sphere of influence was approximated using the following relation:

$$R_{SOI} = D \left(\frac{m}{M} \right)^{\frac{2}{5}} \quad (3)$$

where m is the mass of Venus, M is the mass of the Sun and D is the distance between the two planets [3]. In this analysis, both the mothership and the spacecraft were considered as one spacecraft (prior to separation) and possess the same initial conditions at the boundary of Venus's sphere of influence. The parameters discussed above are illustrated in Fig. 1.

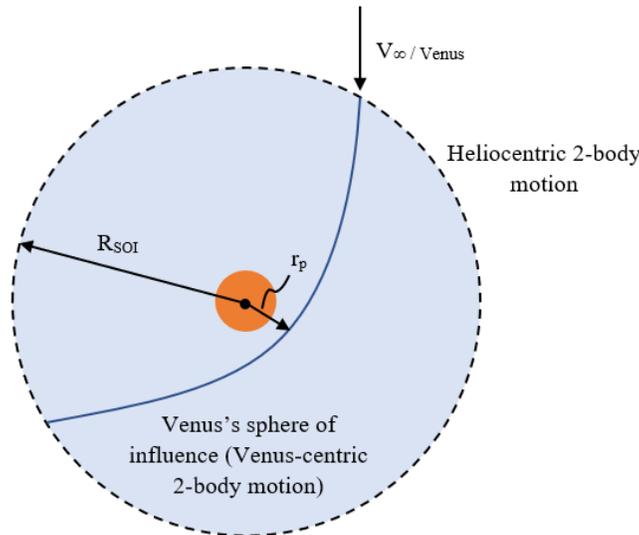


Figure 1. Patched conic trajectory regimes for Venus flyby encounter.

The separation of the probe from the mothership was modelled as an impulsive maneuver along the velocity vector. The separation maneuver was performed at different points along the inbound hyperbolic trajectory to assess its impact on the resulting planetary flyby in terms of the growth in the relative range between the two spacecraft. This was accomplished by delaying the maneuver to occur progressively closer to Venus after propagating the trajectory from the edge of the sphere of influence. The necessary delta-v to yield the desired periapsis radius of the probe was iteratively solved for each case.

Probe Thermal Environment

The probe's survivability will be put to the test during its encounter with the harsh environment of Venus as it dips to an altitude of just 120 km. The structural and thermal integrity of the aeroshell is paramount to the protection of the spacecraft bus and payload (spectrometer) and hinges upon the thermal protection system (TPS). The TPS for Cupid's Arrow consists of the heat shield (forebody) and backshell (aftbody). Continuing in the footsteps of previous planetary entry missions, Cupid's Arrow's atmospheric probe (shown in Fig. 2) utilizes a 45-degree (half-angle) sphere cone heat shield design.

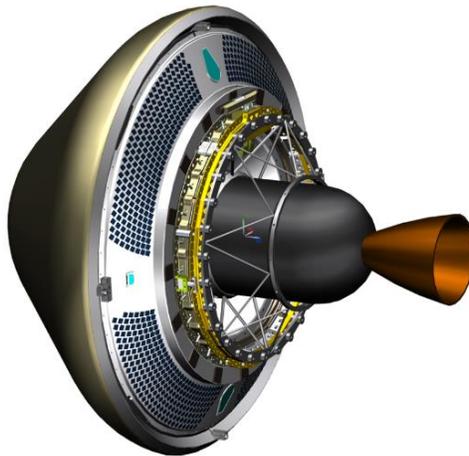


Figure 2. Cupid's Arrow preliminary CAD model [4].

With the size and shape of the aeroshell determined, the next phase of the TPS system design was the selection of the TPS that would be used to coat the heat shield. The two primary metrics used to choose and size the TPS coating are the maximum heat rate and total heat load that the probe would experience. The former determines the choice of TPS material that lines the heat shield while the latter is used to size the lining's thickness. The heat rate is the instantaneous heat flux at a point on the vehicle while the heat load is the integrated heat rate over the trajectory [5]. Using simple planar equations of motion, the probe's descent into the Venusian atmosphere was simulated to characterize its thermal environment [5]. The following atmospheric relative equations describe the entry trajectory of the probe in terms of its velocity, flight path angle and altitude. This unpowered entry trajectory (like most planetary entry missions) is largely driven by the three following design parameters: (1) Flight path angle, (2) Ballistic coefficient, (3) Lift to drag ratio.

$$\frac{dV}{dt} = \frac{-\rho V^2}{2\beta} + g \sin(\gamma) \quad (4)$$

$$V \frac{d\gamma}{dt} = -\frac{V^2 \cos\gamma}{R_p + h} - \frac{\rho V^2}{2\beta} \left(\frac{L}{D}\right) + g \cos(\gamma) \quad (5)$$

$$\left(\frac{dh}{dt}\right) = -V \sin(\gamma) \quad (6)$$

Besides planar motion, the set of equations above also inherit the following assumptions: (a) Spherical planet, (b) Negligible rotational velocity of Venus, (c) Negligible wind effects, (d) Constant mass of entry vehicle [5]. In order to solve the equations defined above, the gravity and atmospheric density were modelled as the following functions as a function of altitude.

$$\rho = \rho_0 e^{-\frac{h}{H}} \quad (7)$$

$$g = g_0 \frac{(R_p^2)}{(R_p + h)^2} \quad (8)$$

The values of ρ_0 and H were based on the Venus International Reference Atmosphere (VIRA) model [6]. The nominal entry conditions for the atmospheric entry trajectory simulation (Table II) were derived from the probe's radius and velocity at periapsis following the separation maneuver.

Using the velocity information, the stagnation point convective heat rate of the probe during the entry regime was determined using the Sutton-Graves equation shown below where the value of k is $1.8960e-4$ for Venus [5]. This relation assumes that the probe's outer surface is fully catalytic. For the purpose of this study, the radiative heating effects can be ignored due to the moderate entry velocity (~ 10.5 km/s). The total heat load experienced by the probe is integrated heat rate over the trajectory.

$$q = k \left(\frac{\rho}{r_n}\right)^{\frac{1}{2}} V^3 \quad (9)$$

RESULTS

Probe and Mothership Relative Trajectory

The initial conditions used for the Venus flyby simulation listed in Table I were used to generate the following range, velocity, altitude and trajectory plots for the relative motion between the probe and mothership.

Table I. Initial conditions for hyperbolic flyby simulation.

V_{arr}	37.7267 km/s
$V_{\infty/Venus}$	2.7066 km/s
r_{SOI}	616282 km

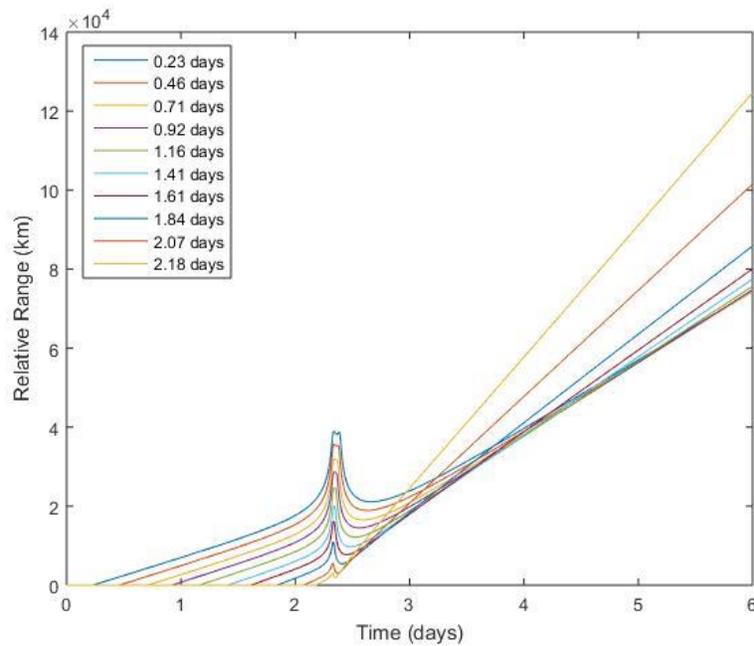


Figure 3. Time history of relative range between the probe and mothership during Venus flyby encounter for different separation times.

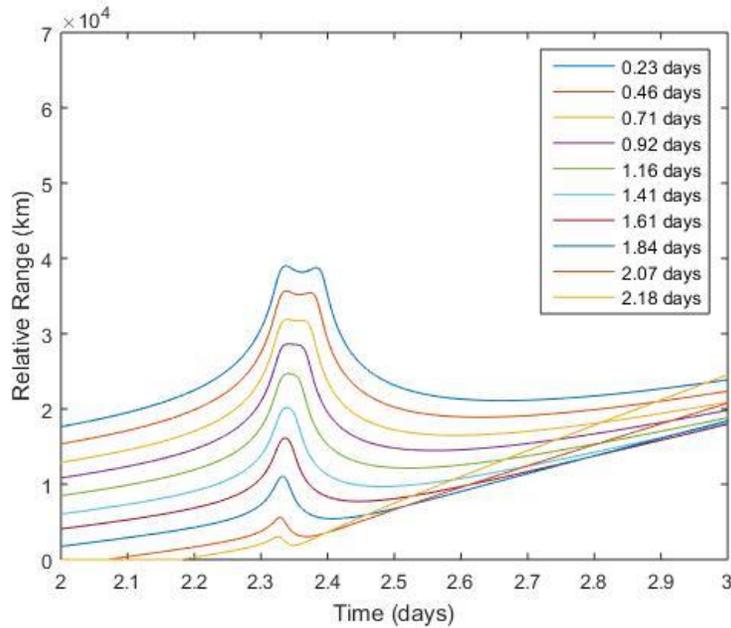


Figure 4. Zoomed in view of the relative range profiles in Fig. 3.

Figures 3 and 4 and show that delaying the separation of the probe from the mothership has the benefit of reducing the spike in the relative range during the Venus encounter. Since the probe experiences a greater gravitational acceleration to Venus than the mothership, delaying the separation maneuver prevents the relative range from building up too quickly. A delayed probe separation also incurs a greater maximum relative range well beyond the planetary encounter which can be dismissed for the purpose of this analysis. A more important downside that must be taken into consideration is the additional fuel cost that is required to carry out the maneuver later in flyby trajectory. As of the writing of this paper, the baseline probe design includes X-band antennas that give it the capability to downlink data directly to Earth via the Deep Space Network (DSN) as a contingency if the mothership is out of range.

The results of the above analysis showed that the probe separation maneuver performed 2.18 days after entering the sphere of influence of Venus produced the most desirable relative range profile between the two spacecraft for communications purposes. The delta-v needed to perform the maneuver was calculated to be 0.1699 km/s. For the reader's reference, the periapsis encounter of the probe takes place approximately 2.3 days into the trajectory. Figures 5, 6, 7 and 8 were generated using the best-case probe separation maneuver.

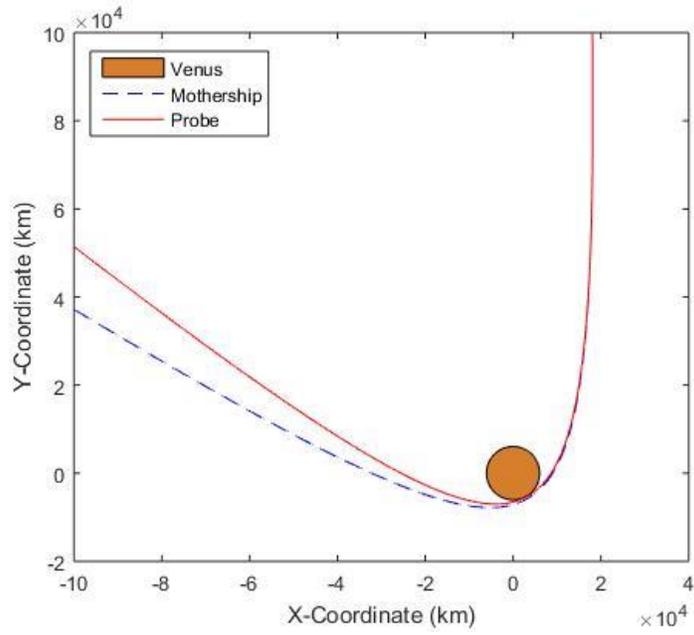


Figure 5. Venus flyby trajectory of the probe and mothership.

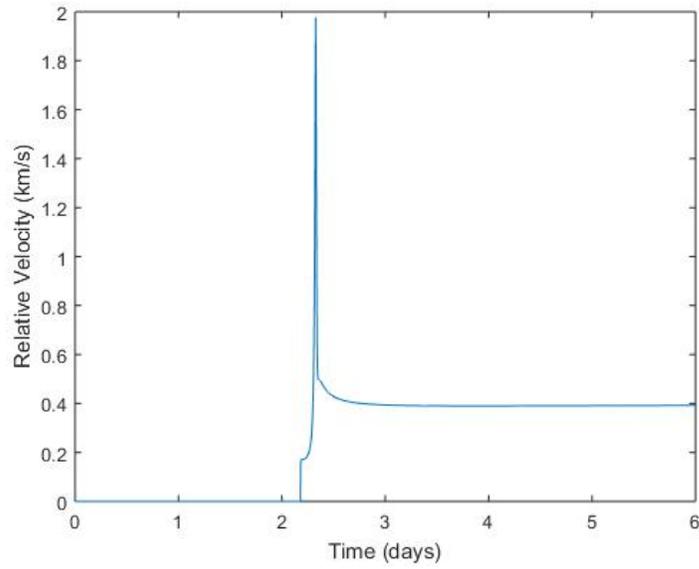


Figure 6. Relative velocity profile of the Venus flyby encounter.

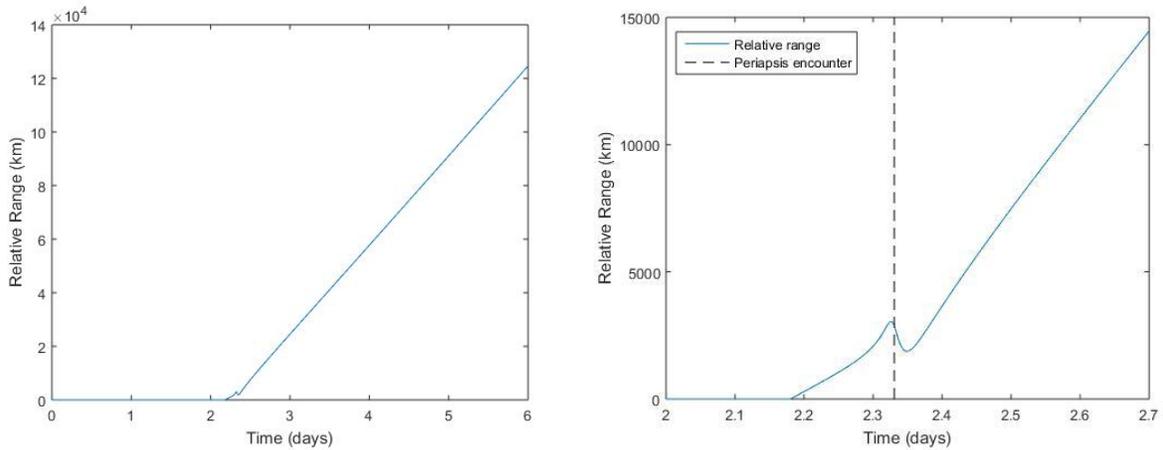


Figure 7. Relative range profile of the Venus flyby encounter.

The Venus flyby shown in Fig. 5 is broken into three distinct phases: pre-separation, periapsis encounter and post-separation. As expected, the peak relative velocity (see Fig. 6) occurred during the second phase and was determined to be 1.9764 km/s. After the flyby, the velocity of the spacecraft with respect to one another reached a steady state value of about 0.4 km/s. Both spacecraft remain relatively close following the separation maneuver with a gradual increase in the range between them as shown in Fig. 7. Immediately following the probe’s periapsis passage, the range decreases a little before quickly building up due to the different turn angles of each spacecraft. The range plots show that the two spacecraft remain within 10000 km of each other for approximately 0.2403 days or 346 minutes after the probe’s periapsis encounter which is ample time for it to relay the science data to the mothership. However, it must be noted that the time required for the analysis of the collected gas samples was assumed be on the order of minutes. The altitude profile of the simulated flyby in Fig. 8 shows that the target altitude of 120 km was achieved.

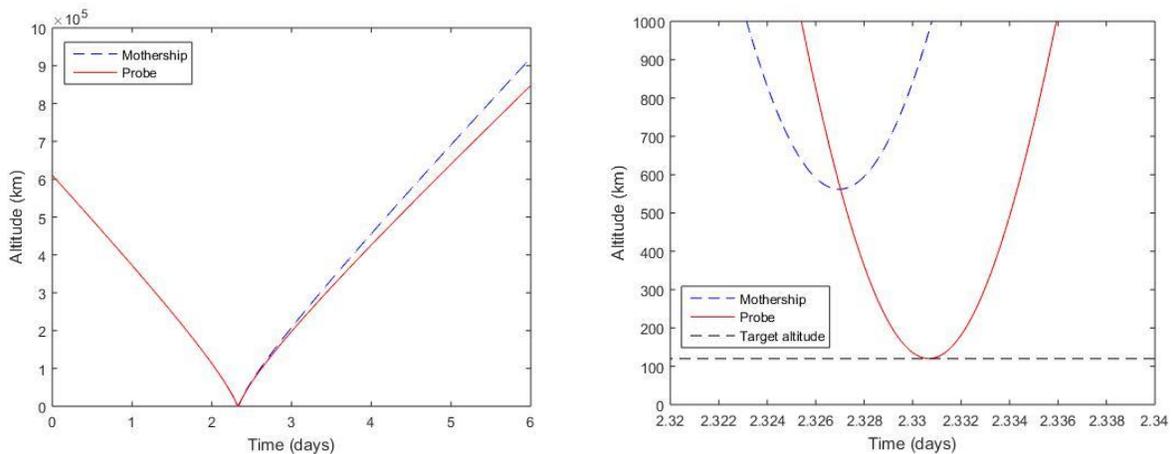


Figure 8. Mothership and probe altitude profile of the Venus flyby encounter.

Probe Thermal Environment

Table II. Atmospheric entry boundary conditions.

V_{entry}	10.5 km/s
γ_{entry}	7.5°
h_{atm}	200 km

Table III. Current best estimates of the probe design parameters.

L/D	0.1
C_d	1.12
m_{probe}	72.8
d_{probe}	0.87 m
r_n	0.44 m
β_{probe}	109.34 kg/m^2

Using the initial conditions and design parameters listed in Tables II and III, the following trajectory, acceleration (in Earth g's) and heating plots were generated for the probe's atmospheric entry. The drag coefficient used was based on the Hayabusa mission which used the same aeroshell design [2]. The L/D was chosen with to produce the desired atmosphere-skimming maneuver and minimize the thermal loads.

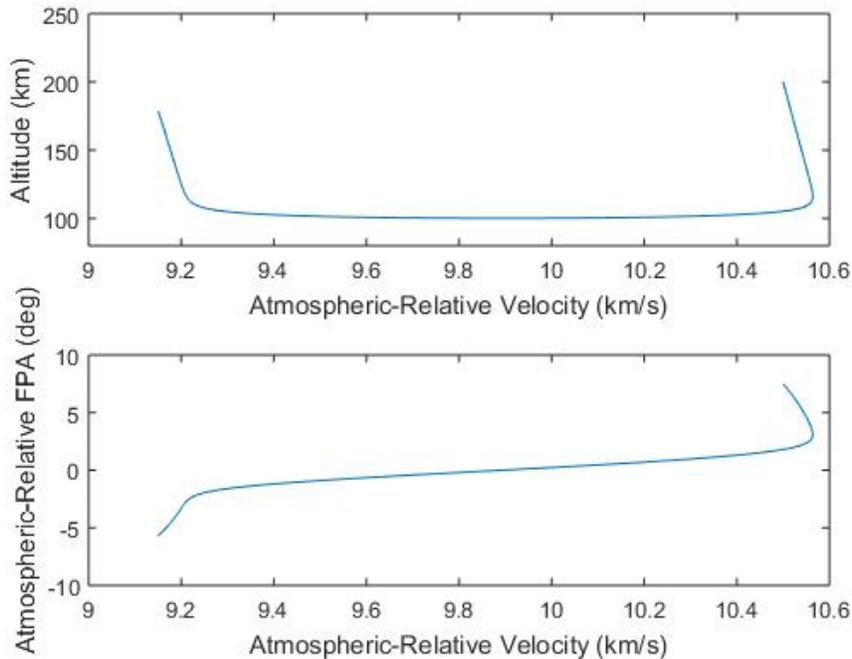


Figure 9. Altitude (top) and flight path angle (bottom) as a function of velocity.

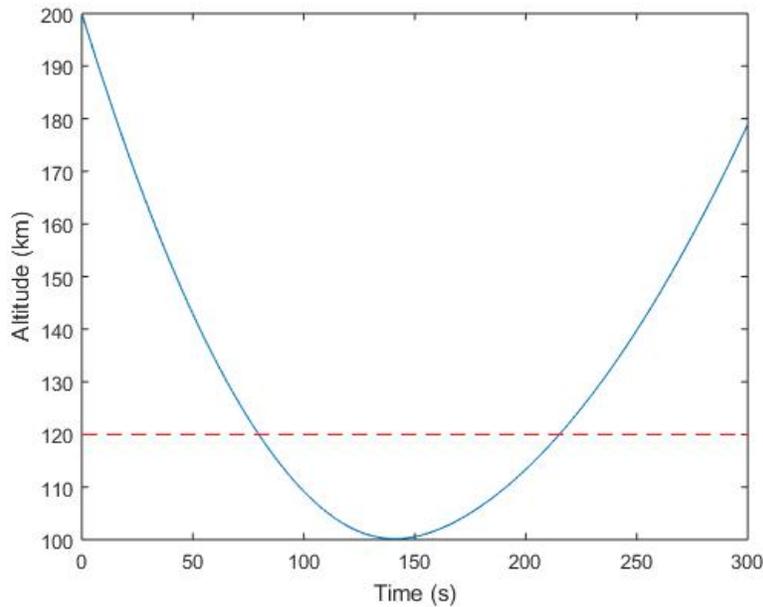


Figure 10. Altitude profile of the probe during entry.

The simulated entry trajectory in Fig. 9 shows the probe maintaining a constant altitude of around 100 km during the peak deceleration phase before ‘skipping’ out of the atmosphere. The altitude at which peak deceleration occurs is primarily driven by the density of the target planet’s atmosphere. The atmospheric density on Venus is much greater than on Earth which causes the probe to decelerate at a higher altitude. This trajectory is favorable for the primary science mode of the mission during which the sample acquisition occurs. The altitude profile in Fig. 10 shows that the probe remains below the target altitude for approximately 136 s which is more than adequate time for sufficient gas samples to be collected for on board analysis. The orientation of the spacecraft is represented by the flight path angle plot which shows the probe transition from having positive FPA angles (atmospheric entry) to negative angles (atmospheric exit).

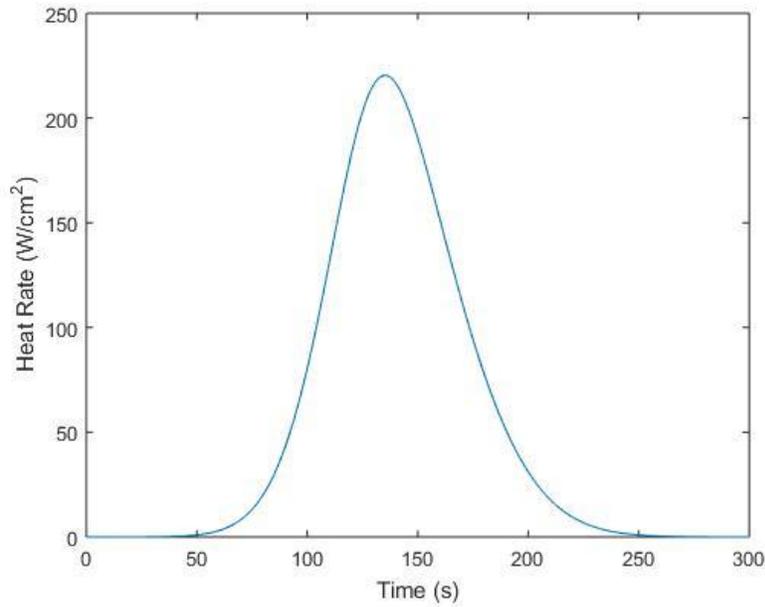


Figure 11. Stagnation point convective heating profile of the probe during entry.

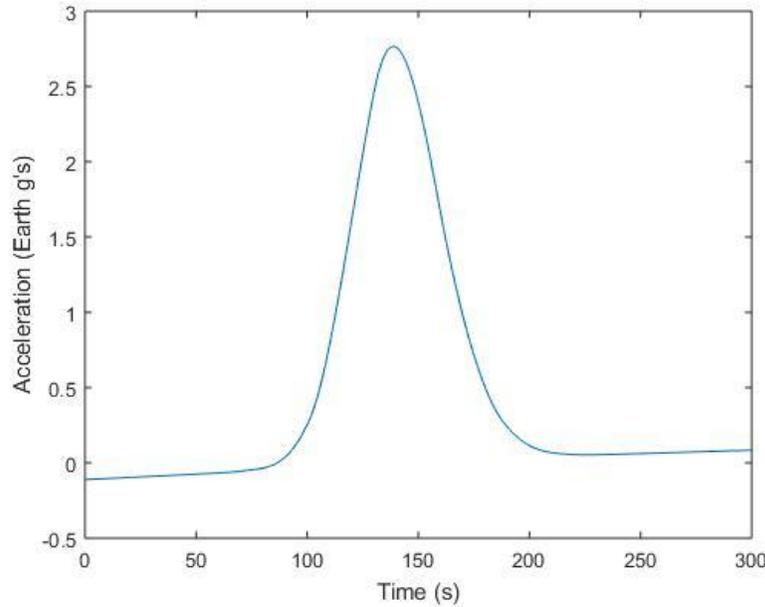


Figure 12. Acceleration profile of the probe during entry.

Figure 11 shows the heat rate profile of the probe determined using the Sutton-Graves relation (Eq. 9) discussed earlier. The peak stagnation point convective heat rate and the total integrated heat load were calculated to be 220.3297 W/cm^2 and 15535 J/cm^2 respectively. The peak heat rate is well within the limit of the current baseline TPS material, PICA which can handle heat rates over 1500 W/cm^2 [4]. PICA is a relatively low density ablative material developed by

NASA Ames Research Center for use on the Stardust Return Capsule [7]. Since then, it has been used for the Mars Science Laboratory mission and the Dragon spacecraft (SpaceX uses its own version of PICA called PICA-X). The required thickness of the heatshield is driven by the maximum bondline temperature which directly impacts the internal components of the spacecraft. The bondline temperature is the temperature of the heatshield surface on which the PICA tiles are adhered to. As shown in Fig. 12, the spacecraft experiences a surprising low maximum structural load of 2.7654 Earth g's during the peak deceleration region. This is largely due to the nature of the trajectory that merely skims the atmosphere instead of passing through the bulk of it.

CONCLUSION & FUTURE WORK

The initial results of the thermal environment and trajectory analyses of the Cupid's Arrow atmospheric probe validate the feasibility of the mission concept. The stagnation point convective heat rate and total integrated heat load are well within the constraints of existing heritage TPS systems. Furthermore, the study suggests that the desired relative motion between the two spacecraft can be achieved by performing a relatively inexpensive and simple burn at the right point along the trajectory. This study has demonstrated the attractiveness of using interplanetary flybys to drop-off small satellites at another planet. This concept adds scientific value to the primary mission by leveraging its infrastructure at a fraction of the cost of an entirely separate mission [8]. Planets like Venus – that are often used for gravity assists – or even the moons of Saturn that were passed by Cassini are perfect for this method of deployment. Add this to the fact that most interplanetary mission have unused mass margin, the implementation of this model to study planetary atmospheres is an endeavor worth pursuing in the near future.

This study focused on the conceptual design and feasibility analysis of Cupid's Arrow as a potential future NASA mission. If additional funding can be procured, a higher fidelity 6-DOF orbit propagator like NASA's POST2 which includes atmospheric drag, solar radiation pressure and other 3rd body perturbations will be implemented to accurately characterize the trajectory of both spacecraft. In addition, a more complex thermal model and/or thermal environment simulation tool (e.g. Thermal Desktop or Siemens NX) should be used to size the TPS system (i.e., determine the thickness of the PICA heatshield). A comprehensive full body three-dimensional CFD model of the simulated probe entry would also be required to determine the specific TPS requirements of different sections of the spacecraft. The effects of non-Hohmann type transfer trajectories on the arrival conditions at Venus are also worth exploring. This study did not include any trajectory optimization scheme which could be used in future studies to fine tune the reference trajectory for control purposes as well as to mitigate the heating effects on the probe.

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