Assessing Huygens Probe Entry, Descent, and Landing at Titan Simulation using Dragonfly Atmosphere Model

Alejandro R. Pensado*, Caleb Robb†, Richard Winski‡, James Williams†
Analytical Mechanics Associates, Hampton, VA, 23666, USA

Michael W. Belair§
NASA Langley Research Center, Hampton, VA, 23681, USA

Ralph D. Lorenz¶
Johns Hopkins Applied Physics Laboratory, Laurel, MD, 20723, USA

Dragonfly is a New Frontiers Program mission that will deliver a rotorcraft to Saturn's moon, Titan. This mission follows Huygens as the previous mission that successfully landed a vehicle on Titan. A flight mechanics simulation of Dragonfly's Entry, Descent, and Landing sequence has been developed using the Program to Optimize Simulated Trajectories II. The simulation incorporates several subsystem models, including aerodynamics, gravity, and mass properties, to fully capture the multi-body six degree of freedom dynamics. Among all the subsystem models that inform the Entry, Descent, and Landing dynamics, the atmosphere model of Titan is a critical component. The atmosphere model characterizes the density, temperature, pressure, and winds that the entry vehicle experiences during the descent. This impacts several aspects of the descent such as the peak heating, aerodynamics, parachute release conditions, the dynamics of the vehicle and parachutes, and the landing ellipse. In the course of developing Dragonfly, an updated model of the Titan atmosphere has been created corresponding to Dragonfly's arrival in the mid-2030s, approximately one Titan year after the Huygens mission successfully landed a probe on Titan. This work leverages previous work done to investigate Huygens EDL sequence to assess the atmosphere model developed for Dragonfly. This is done by utilizing the updated Titan atmosphere model, the Dragonfly atmosphere model, within the Huygens POST2-based flight simulation with the goal of characterizing the differences between the atmospheric models and assessing how the Dragonfly atmosphere model impacts Huygens entry dynamics.

I. Introduction

Dragonfly is a New Frontiers Program mission that will deliver a rotorcraft lander to Saturn's moon, Titan [1]. The Entry, Descent, and Landing (EDL) sequence is a critical part of the mission and is modeled using the Program to Optimize Simulated Trajectories II (POST2) [2]. POST2 is a a six degree-of-freedom, rigid-body flight dynamics simulation that can simulate trajectories for multiple bodies. This simulation incorporates planet, vehicle, aerodynamics, parachute, and atmospheric models to characterize the vehicle dynamics and assess against mission requirements as seen in Figure 1 [3].

A key model required to characterize the dynamics of the EDL sequence is the atmosphere of Titan. Atmospheric models include nominal and dispersed data on density, temperature, pressure, and wind patterns experienced by the entry vehicle throughout its descent. These factors influence key descent metrics, including peak heating, aerodynamics, optimal conditions for minimizing the total angle of attack at drogue release, and the behavior of the vehicle and parachutes, including the main parachute pressure release mechanism. In contrast to Mars missions with seven minutes of EDL, the descent on Titan spans over two hours due to Titan's dense atmosphere, which significantly affects the lander's release ellipse. Validating the atmospheric model is critical.

The Huygens mission, which landed January 14, 2005, aimed to collect in situ measurements of Titan. Onboard instrumentation and a camera have driven much of what is known about the composition of Titan's atmosphere, geology,

*Aerospace Engineer, Atmospheric Flight and Entry Systems Branch, MS 489, Senior AIAA Member.
†Aerospace Engineer, Atmospheric Flight and Entry Systems Branch, MS 489, AIAA Member.
‡Aerospace Engineer, Atmospheric Flight and Entry Systems Branch, MS 489, AIAA Associate Fellow.
§NASA OSTEM Intern
¶Principal Professional Staff, Space Exploration Sector, AIAA Member

and geography. The Dragonfly project has aimed for an arrival date that corresponds with one Titan year [4] to leverage much of that atmospheric data to create an updated model that corresponds to some of the conclusions drawn from the flight data. The focus of this work is aimed at approximating the Huygens trajectory with many of the models that were published leading up to, and immediately after, the descent and then reproducing the simulation with the only difference being the atmosphere model utilized. The atmosphere model used in the first simulation is from Titan GRAM, a Fortran based engineering model that is widely available to the public [5]. The focus of this work was not to directly compare the atmosphere models themselves, as it is well established in literature that Titan GRAM needs to be updated [6], but to highlight the differences in vehicle behavior that arises due to the updated model. Instead the focus here is how the Dragonfly atmosphere could improve a match between simulation predictions and Huygens flight data.

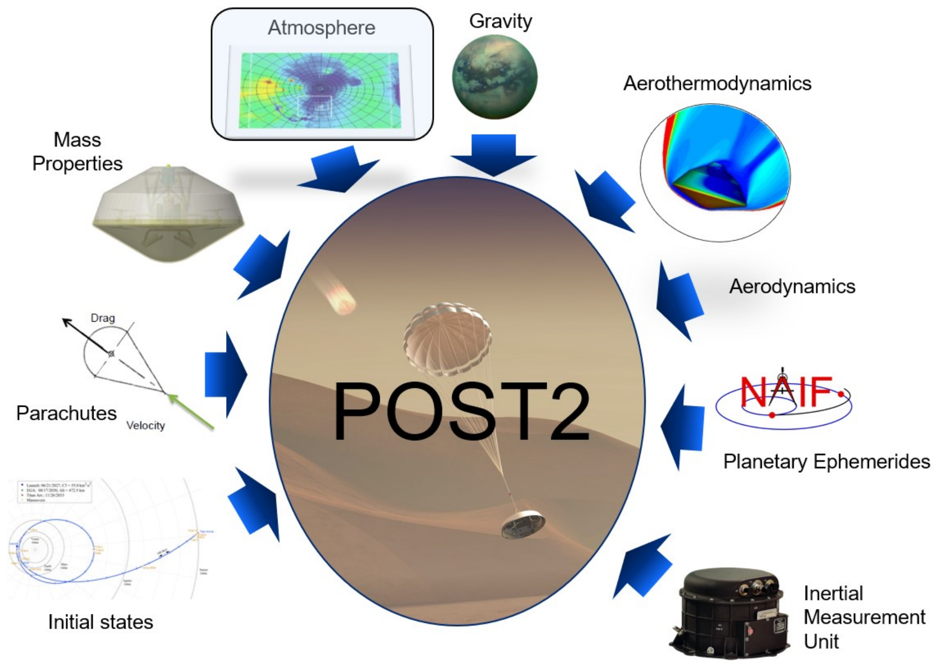


Fig. 1 POST2 Dragonfly Subsystem Model Overview

II. Huygens Concept of Operations

The EDL Concept of Operations (ConOps) used in this study is the consistent with the sequence used in reconstruction efforts of the Huygens trajectory[7]. The start of the sequence begins at the atmospheric interface, 1270 km altitude. During the probe's descent, the sequence is based on a timer started when the mortar is deployed and the pilot chute is pulled out. At heatshield jettison, the scientific instrumentation, as well as spin vanes on the probe, were exposed and science collected. The trajectory took a very long time relative to other planetary probe missions, about 2.5 hours from atmosphere entry to landing. The first 300s of this was spent in free fall before the acceleration trigger that began the main sequence, starting with the pilot parachute deployment.

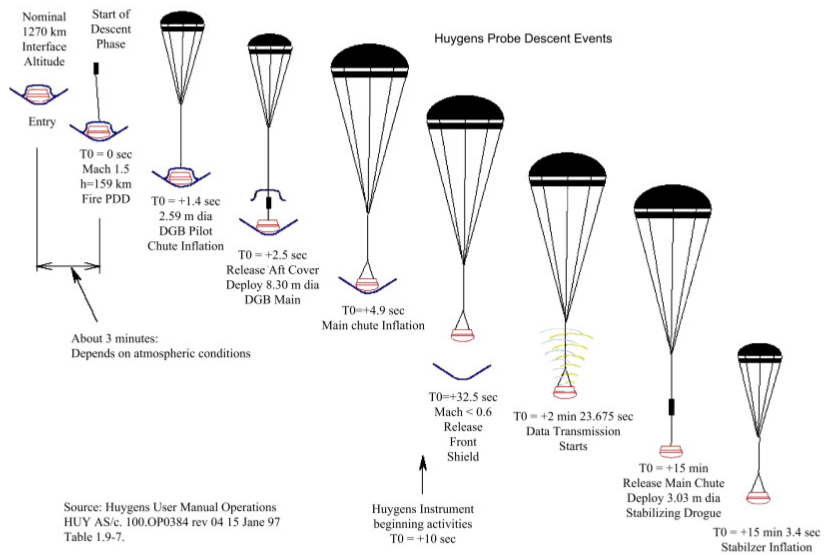


Fig. 2 Huygens EDL Sequence Overview[7]

The pilot parachute deploy command was triggered when the sensed acceleration was less than 10 m/s^2 and declining. When the pilot deploy command was triggered, there was a delay of 6.375 seconds before the chute was actually deployed and a further 1.4 seconds before the parachute was assumed to be inflated. The acceleration trigger and deploy delay are taken from project documentation and sources from within the project. The inflation delay is shown on Figure 2 as a project assumption. Notably, the deployment of the pilot chute began the descent timer that dictated the rest of the events in the sequence. The rest of the timings are shown in that figure, with the POST2 simulation following this sequence and modeling every event with the exception of data transmission.

The entry sequence has been documented in Table 1, referencing both a time since acceleration trigger (AT) and parachute descent time (DT). The traditional time zero point for the probe in literature aligns with the parachute descent time, with this being when the mortar is deployed and the pilot chute is pulled out. The timer that starts at Time DT equal to zero controls the rest of the EDL sequence, including the other parachute deployment timings and heatshield jettison time.

Table 1 EDL Event Sequence

Event	Criteria	Value
Entry Interface	Altitude (km)	1270
Pilot Deploy Trigger	Sensed Acceleration (m/s^2)	10
Pilot Deploy	Time AT (s)	6.375
Pilot Inflation	Time DT (s)	1.4
Main Deploy	Time DT (s)	2.5
Main Inflation	Time DT (s)	4.9
Heatshield Jettison	Time DT (s)	32.5
Stabilizer Deploy	Time DT (s)	900
Stabilizer Inflation	Time DT (s)	903.4

III. Atmosphere Models

Atmosphere models for the Dragonfly project are maintained by the Mission Architect (R. Lorenz) and maintained under configuration control under the project's Environment Requirements Document (ERD). The model specifications include minimum, nominal, and maximum winds, temperature, and density as a function of altitude, together with composition data. The basic features of the model as specified through mission Preliminary Design Review (PDR) in early 2023 are described in Reference [1]. The nominal density/temperature profile is that measured by the Huygens probe, and the fact that Dragonfly will enter the Titan atmosphere at a comparable near-equatorial latitude and near-identical season allows much spatial and temporal variation to be excluded.

The zonal wind profile, which substantially drives the East/West size of the landing ellipse, is similarly specified to be that measured by Huygens. The Dragonfly model is curated with updates as new information arises from new analyses or observations. An update since Reference [1] is due to new high-altitude zonal wind measurements from the Atacama Large Millimeter Array. Previously, the winds above 250 km were just assumed to be constant with altitude. Associated with that update, the winds have been specified as piecewise linear profiles – this makes for a more transparent relationship of the model to results than the ad-hoc smooth algebraic functions used in Reference [1]. Minor adjustments have also been made to the temperature profile with altitude. A more detailed description of the updates and their scientific rationale will be given in a future publication.

As a benchmark case, simulations of the Huygens entry and descent with the models in Titan-GRAM-2004 were examined. The Global Reference Atmosphere Model (GRAM) framework is used to maintain and deliver models for EDL and other studies on a variety of planetary bodies such as Mars, Venus, and Earth. The Titan-GRAM-2004 model was constructed prior to the emergence of Cassini-Huygens results [8]. As noted in mission studies almost a decade later [6], some aspects of Titan-GRAM-2004 are over-conservative, notably the meridional wind dispersion. Additionally, some aspects such as the cold mesosphere at about 600 km were not substantiated by Huygens data. Nonetheless it makes a useful basis for comparison, and given the austere pre-Cassini basis for its formulation, is generally reasonable. It should be noted that the GRAM suite is presently being updated, and so it should be understood that these remarks apply to the Titan-GRAM-2004 version only, a new version will incorporate many features of the Dragonfly model. Therefore it is highly recommended that GRAM not be referred to without the associated update year.

One important difference between the Dragonfly zonal wind profile and that in Titan-GRAM-2004 is that the Huygens Doppler data yielded a strong dip in wind speed at about 70 km altitude, with strong positive and negative wind gradients above and below that altitude, whereas the pre-Huygens model (originally due to M. Flasar, see Reference [6]) had a monotonic profile. This dip has been reproduced in some global circulation models and indicated in other data [9], and thus while not anticipated in pre-Huygens models, is believed to be a real and persistent feature. Another notable difference is the temperature profile above 400 km. The deviations from a constant value seen in individual measurements that produced the Huygens profile are local and transient (e.g. gravity waves) thus a constant temperature is an adequate and succinct description of what may be expected. A comparison of the Dragonfly and Titan GRAM atmosphere models is shown in Figs 3 - 5.

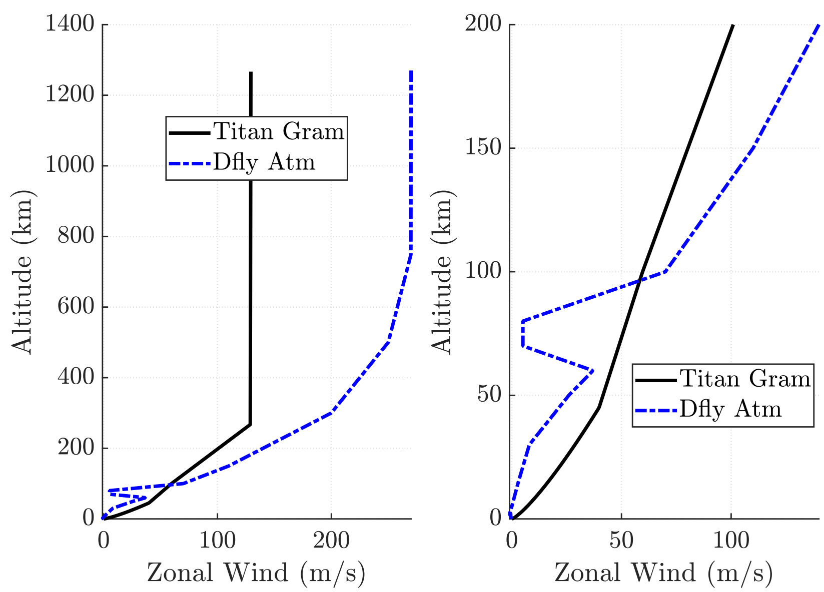


Fig. 3 Titan GRAM vs Dragonfly Zonal Wind Profile

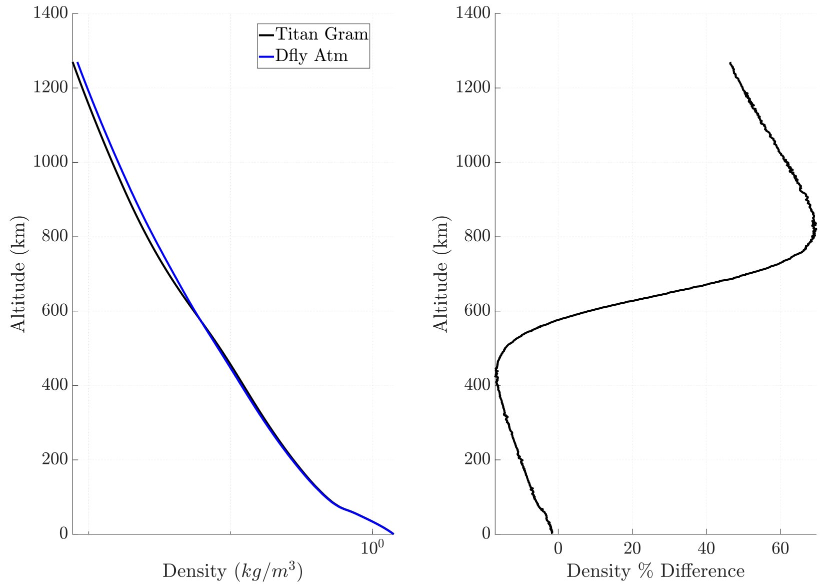


Fig. 4 Titan GRAM vs Dragonfly Density Profile

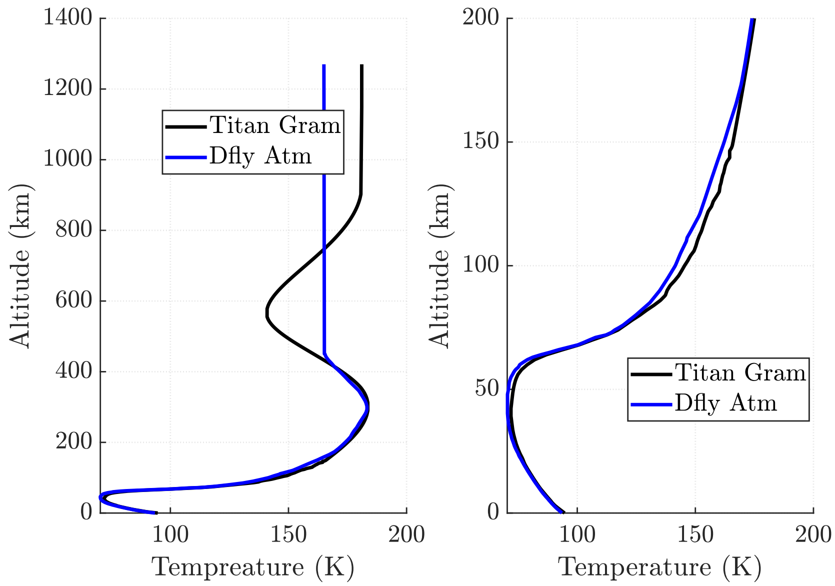


Fig. 5 Titan GRAM vs Dragonfly Temperature Profile

IV. Modeling and Simulation

This paper builds on the Huygens Probe EDL POST2 simulation work done by Striepe et al. [10, 11]. This simulation modeled the Huygens probe using a six degree-of-freedom entry vehicle and a three degree-of-freedom parachute. The simulation incorporated a 6DOF aerodynamics model, a Titan-GRAM atmospheric model, the Dragonfly atmosphere model, and a parachute model. For the gravity model, a simple normalized spherical harmonic model was utilized. Although this 2x2 model is not as complex as the 4x4 model currently in use by the Dragonfly project [12], it is seen as an adequate approximation for the purposes of this study. For the purposes of this study, all the model assumptions are leveraged from the Striepe et al. [10, 11] and only the atmosphere models will be replaced. Further information on Huygens modeling assumptions can be found in [10]. The vehicle is initialized using the same states as shown in Table 2.

Table 2 Initial Inertial States in the Titan-relative frame [10].

Initial States	Units	Value
X	km	-3785.05
Y	km	366.62
Z	km	-568.43
V_x	km/s	5.70
V_y	km/s	1.92
V_z	km/s	0.39
Julian Date	s	2453384.8791700

A. Mass Properties

The mass properties were taken from the Alcatel probe reference data [13]. The values throughout the EDL sequence are taken from a table describing the mass budget at each step, reconstructed in Table 3. The change in mass properties are modeled as instantaneous changes in POST2. The reference point for the mass properties is, for consistency, made to match that of the probe data sheet, Reference [13]. Figure 6 shows the reference point in relation to other parts of the entry system.

Table 3 Entry Vehicle Mass Properties

Property	Units	Entry	Main Deploy	Heatshield Jettison	Stabilizer Deploy
Mass	m	318.62	287.6	206.91	201.51
Xcg	m	0.08	0.07	0.08	0.07
Ycg	m	0.00	0.00	0.00	0.00
Zcg	m	0.01	0.01	0.00	0.00
I_{xx}	kg$\cdot m^2$	126.17	113.20	38.60	38.23
I_{yy}	kg$\cdot m^2$	74.63	66.00	25.62	24.71
I_{zz}	kg$\cdot m^2$	71.57	63.19	23.61	22.70
I_{xy}	kg$\cdot m^2$	0.45	0.44	-0.02	0.06
I_{xz}	kg$\cdot m^2$	0.10	0.02	-0.06	-0.02
I_{yz}	kg$\cdot m^2$	-0.34	-0.34	-0.46	-0.46

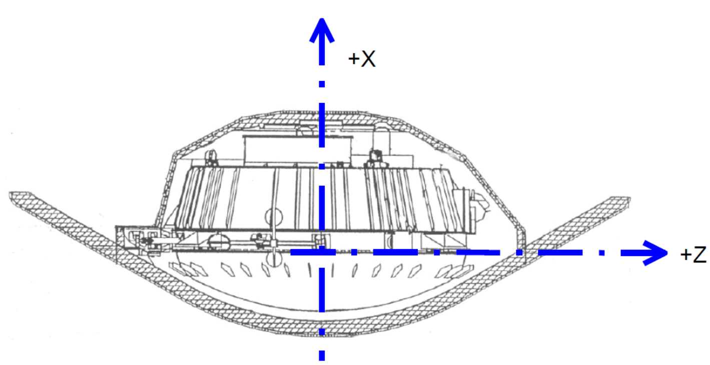


Fig. 6 Huygens Mass Properties Reference Point [13]

There is shown to be a sizable change in mass properties between the entry and main deploy stages. While a portion of this can be attributed to the loss of the pilot parachute system, including the mortar, the rest of the expected mass loss has traditionally been modelled as ablation, shown in Equation 1.

$$M = M_0 * e^{2\sigma(V^2(t) - V_0^2))} \quad (1)$$

Where σ is a mass evolution coefficient estimated at about 4.18E-10 s^2/m^2. The entire mass lost throughout entry is about 9.7 kg. It should be noted, however, that this mass likely would not have been lost solely due to ablation, with the majority of that mass budget assigned to pieces that would more likely fall off at once, such as the multi layer insulation (MLI), due to a dynamic pressure or heat rate limit. This model was developed to characterize the mass loss, though accelerometer data may indicate that mass was lost in more discrete steps [14]. For this work, the equation above is used, although the timing of a step change in mass would be a sensitivity that could be later examined.

B. Entry Module and Probe Aerodynamics

The aerodynamics database was taken from a summary report published by Alcatel, Ref [15]. Summary reports and data are publicly available through the NASA Planetary Data System [16]. This report gives axial and normal force coefficients, as well as the pitching moment and pitch damping coefficients for the entry module and descent probe as a function of angle of attack and either Reynolds Number or Mach Number. The force coefficients for the entry module are shown in Figure 21 as function of Mach number for lines of constant total angle of attack. The probe aerodynamics refer to the aerodynamics on the system post-heatshield jettison. These are taken from the same source as the descent module but are documented as a function of Reynolds Number instead of Mach Number. The tables cover a large Reynolds number regime, although there is not much variance in the coefficients above a Reynolds Number of 250,000. The plotted aerodynamics database is documented in the appendix.

The spin rate of the Huygens probe was of particular note due to the divergence from expected behavior. The probe itself utilized spin vanes, shown in Fig 6 the tabs below the Z axis, to set a spin rate necessary for the instrumentation on the probe. The requirement, and expectation, was for a positive spin rate that would increase at the main-to-stabilizer parachute transition before leveling off to a small positive number. However, during the probe descent, it was shown that the spin rate reversed direction to a comparable magnitude of the expected positive value [17]. During a set of close-out activities aimed at describing the aerodynamics of the descent probe more completely, it was determined that, with all of the instrumentation added to the probe, both an increase in drag coefficient could be expected and an interaction between the spin vanes and instrumentation systems could lead to a reversed roll rate [18]. Data for the roll moment coefficient was then used and roll damping was added and the values for these were tuned to fit the flight data.

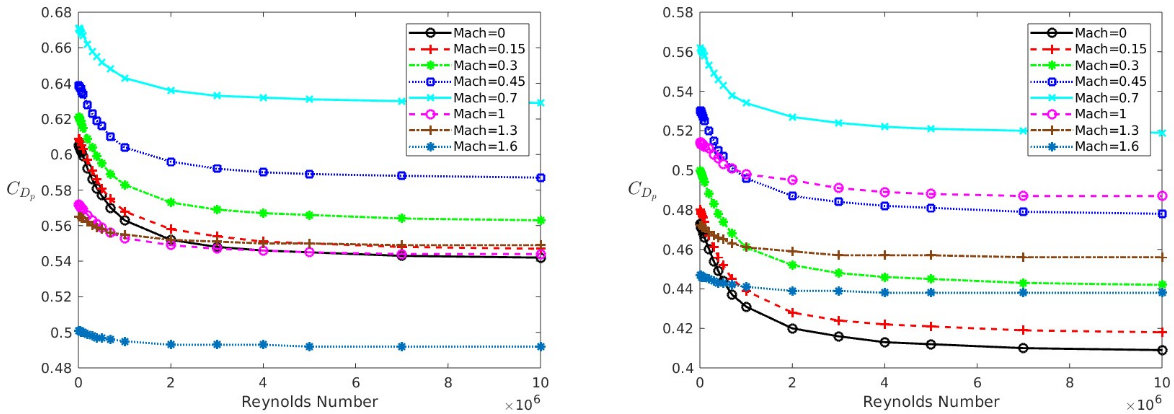
C. Parachute Model

The parachute is implemented in the POST2 simulation as a simple drag addition to the entry module or probe. As Figure 2 shows, there are a total of three parachutes throughout the EDL sequence. The first of these deploys off of an acceleration trigger that starts the timer that all of the other sequence events are based off of. The aerodynamics for all three parachutes are taken from a table in the same Alcatel report as the other aerodynamics [15]. Although the same table is used for all of the parachute drag coefficients, a few approximations were necessary to use this data for the pilot chute. The report specifies that the data reported is for a geometric porosity of 22.4% for the main and stabilizer, which were the second and third parachutes. However, the pilot was reported to be at 13.1% geometric porosity. Thus, an approximation was used to scale the drag coefficient of the main chute compared to the pilot as function of the the porosity. The aerodatabase is plotted as a function of Reynolds number for lines of constant Mach Number in Figure 7.

For this analysis, a simple parachute model is used that applies a drag force in the anti-velocity vector where the triple bridles meet the riser as shown in Fig 8. The bridle attachment points are shown in Table 5 as a distance from the reference point in Fig 6.This is appropriate to capture the translational effect the parachute imparts on the vehicle and

Table 4 Parachute Properties

Parachute	Type	Diameter (m)	Geometric Porosity (%)
Pilot	Disk Gap Band	2.59	13.1
Main	Disk Gap Band	8.30	22.4
Stabilizer	Disk Gap Band	3.03	22.4



(a) Pilot Parachute (b) Main and Stabilizer Parachutes

Fig. 7 Parachute Drag Coefficients

model the descent time. However, this assumes the parachute trims at an angle of attack of 0 deg and does not model the rotational dynamics of the parachute. This means the simulation does not fully capture the pendulum motion the parachute imparts on the vehicle. Additionally, the parachute inflation period is not modelled at this time; the drag force is applied only after an approximated inflation time. So, the parachute dynamics during the inflation process cannot be compared well with the flight data.

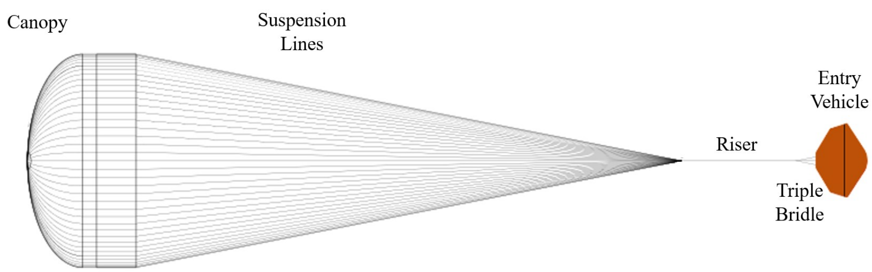


Fig. 8 Parachute Geometry (Not to Scale)

Table 5 Triple bridle confluence point definition along the X Huygens Frame as shown in Fig. 6

Parachute	Bridle Attachment (m)	Bridle Height (m)	Bridle Confluence Point in Huygens Frame (m)
Pilot	0.5572	0.53	1.0872
Main	0.4468	3.88	4.3268
Stabilizer	0.3755	3.88	4.2555

D. Monte Carlo Setup

Monte Carlo analysis was conducted by dispersing the density, atmospheric temperature, and winds. The atmospheric pressure and speed of sound are dispersed as a function of the density and temperature profiles. As mentioned in section III the minimum, nominal and maximum winds, temperature, and density profiles are provided as a function of altitude. The variables are dispersed using the formation described in Equation 2.

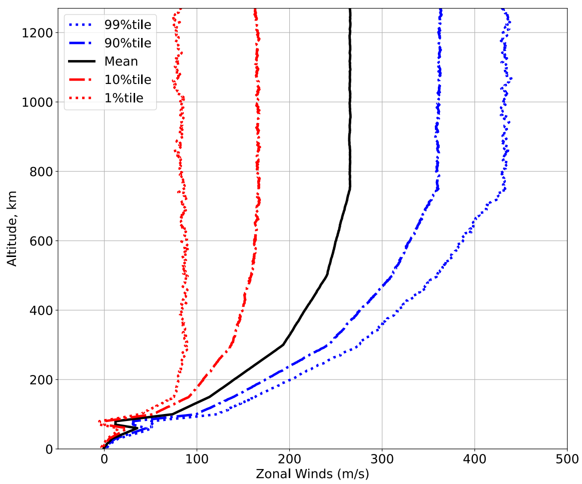
$$x_{disp} = \begin{cases} x_{nom} + \frac{N(0,1)}{\sigma_{99}}(x_{nom} - x_{min}), & \frac{N(0,1)}{\sigma_{99}} < 0 \\ x_{nom} + \frac{N(0,1)}{\sigma_{99}}(x_{max} - x_{nom}), & \frac{N(0,1)}{\sigma_{99}} > 0 \\ x_{nom}, & \frac{N(0,1)}{\sigma_{99}} = 0 \end{cases} \quad (2)$$

The variable x_{disp} is the dispersed variable (temperature, density, zonal wind), controlled by the random variable N(0,1), which is a random Gaussian variate of zero mean and standard deviation of unity and is divided by $\sigma_{99} = 2.32$ to reflect that the minimum and maximum range is 99%. This variable is dispersed for every variable for every case, giving a different input. An example of the inputs for the zonal winds are shown in Table 6. For each run, the random number generated is then used to generate a profile mapped to between the bounds specified.

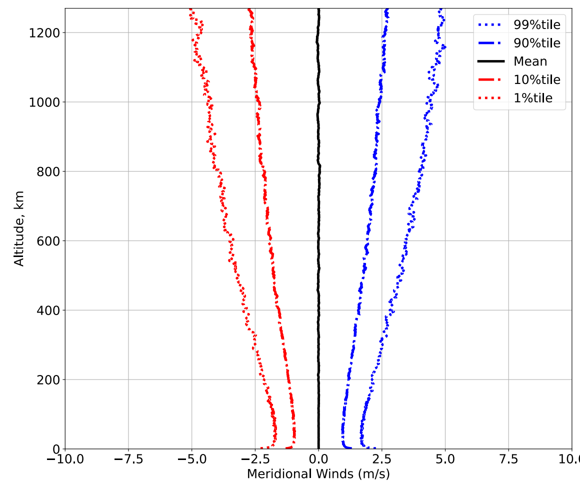
Table 6 Zonal Wind Data

h (km)	U_{min} (m/s)	U_{nom} (m/s)	U_{max} (m/s)
0	-2	0	2
2	-3	-1	2
5	-3	0	3
15	0	3	6
30	5	8	14
50	15	26	40
60	15	37	50
70	0	5	50
80	0	5	50
100	40	70	120
150	80	110	160
300	90	200	270
500	90	250	350
750	90	270	420
1000	90	270	420

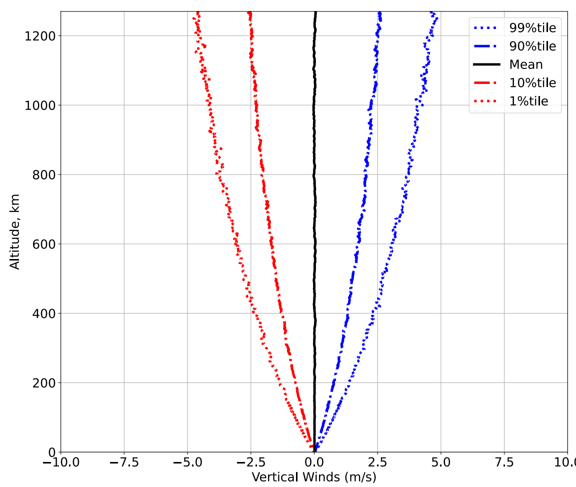
In addition to the dispersions applied to the winds, gust or turbulence profiles are generated for each dispersed profile. The nominal winds do not include gusts profiles. Figs 9 and 10 show a statistical representation of 10,000 dispersed profiles.



(a) Zonal E/W

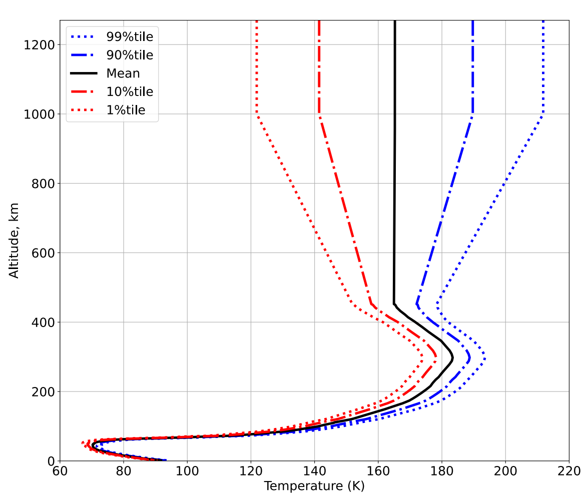


(b) Meridonial N/S

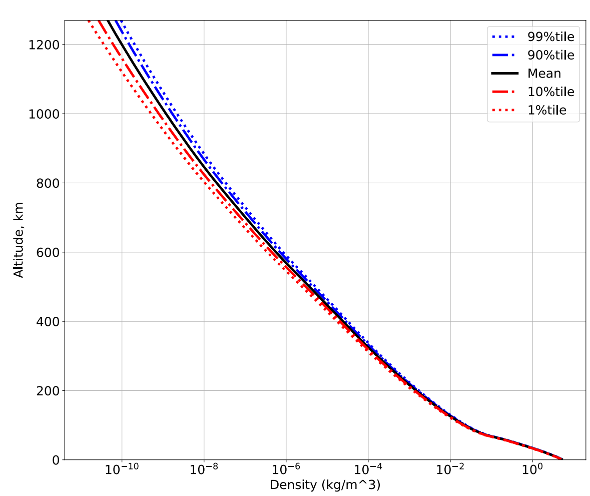


(c) Vertical Wind

Fig. 9 Nominal, 1 %-tile, 10 %-tile, 90 %-tile, and 99 %-tile wind-plus-gust profiles for a) Zonal, b) Meridional, and c) Vertical directions



(a)



(b)

Fig. 10 Nominal, 1 %-tile, and 99 %-tile profiles for a) Temperature and b) Density

V. Results

A. Nominal Time Histories

Nominal trajectories were generated using both atmosphere models and compared with flight data to assess the differences. As mentioned previously, the results are not meant to compare the applicability of the models, but rather to provide context with respect to the Dragonfly atmosphere model. The Huygens probe was outfitted with an accelerometer, labelled as HASI L3 [16] to stay consistent with other documentation, whose data is available to compare throughout descent. Figures 11 and 12 show the difference between that data and the currently constructed simulations using both atmospheres.

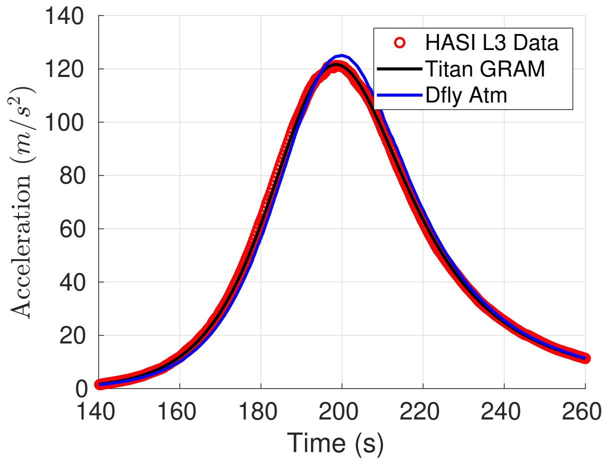


Fig. 11 Acceleration Comparison for Pilot and Main Chute Deployment

During the entry phase of the sequence, the Dragonfly atmosphere case shows a lag for the peak deceleration of about a second and reaching about 4 m/s^2 higher than the Titan GRAM and flight data. Although there is some difference, particularly five seconds after main parachute inflation, the inconsistency is on the order of about 3 m/s^2 as compared to total acceleration of the order of 30 m/s^2, and is seen as acceptable for the purposes of this comparison. The values of the peaks match, including the features associated with the pilot deployment with the simulation results shown to be less noisy compared to the flight data.

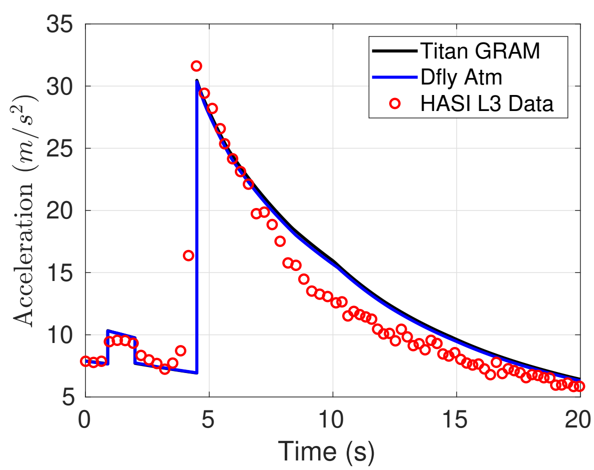


Fig. 12 Acceleration Comparison for Pilot and Main Chute Deployment

The spin rate is seen as a key feature of comparison between the simulations and flight data. As discussed in Section IV.B, the aerodynamics were sourced from a paper aimed at solving the aerodynamics of that issue and then tuned to provide a more representative simulation of the spin rate data, with the current comparison shown in Figure 13. Although the simulated rate of change of the spin rate after the minimum peak is more negative than the flight data, the comparison shows the overall results were sufficient for this study.

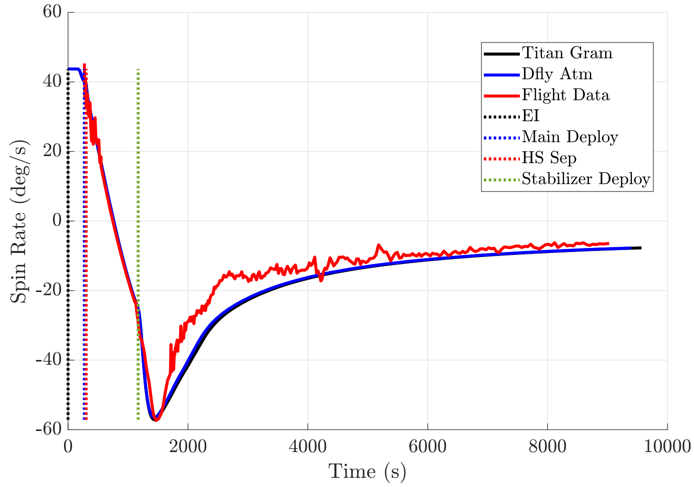


Fig. 13 Nominal Spin Rate Comparison

Fig. 14 shows the overview of the EDL trajectory with the events of interest shown as a function of altitude using both atmosphere models. As noted in Section II the events happen with respect to a timer once the pilot deploy triggers of the sensed acceleration. Since the sensed acceleration occurs at different times, the subsequent events in Fig. 14 happen at slightly different times. The planet-relative velocity during the descent phase shows a difference between the two cases, with higher velocities shown for the Dragonfly atmosphere until the stabilizer parachute is deployed, under which the vehicle spends most of its descent.

Fig. 15 shows the altitude vs planet-relative velocity with and without wind to highlight the impact due the the respective wind models. As expected, the large difference between the models comes from the wind profiles. Furthermore, Fig. 16 shows the relation of planet-relative velocity and density to the altitude. The density for the Dragonfly model is less starting at around 400 km altitude and this trend persists throughout the trajectory. This is shown to be the cause for the higher planet-relative velocity until the zonal winds shift in the Dragonfly model at 100 km.

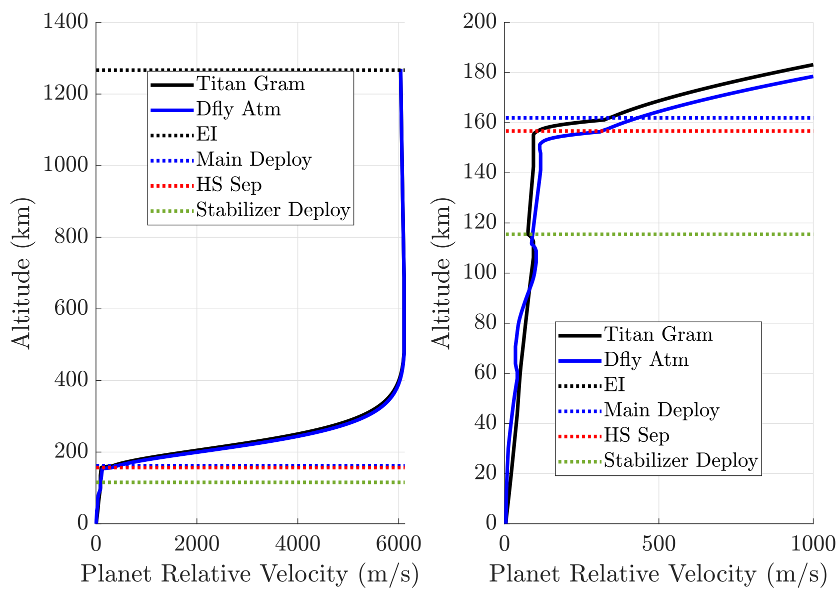


Fig. 14 Nominal Altitude vs Velocity Comparison

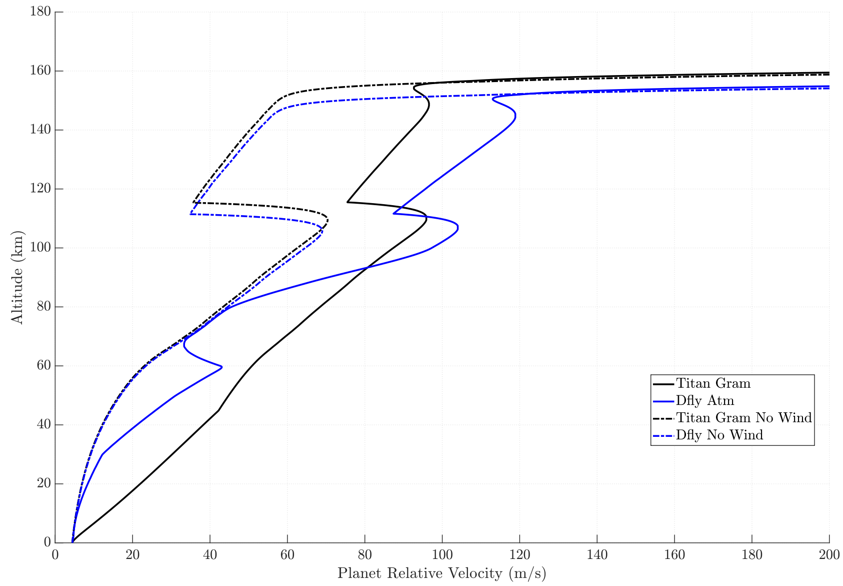


Fig. 15 Nominal Altitude vs Velocity Comparison Wind Sensitivity

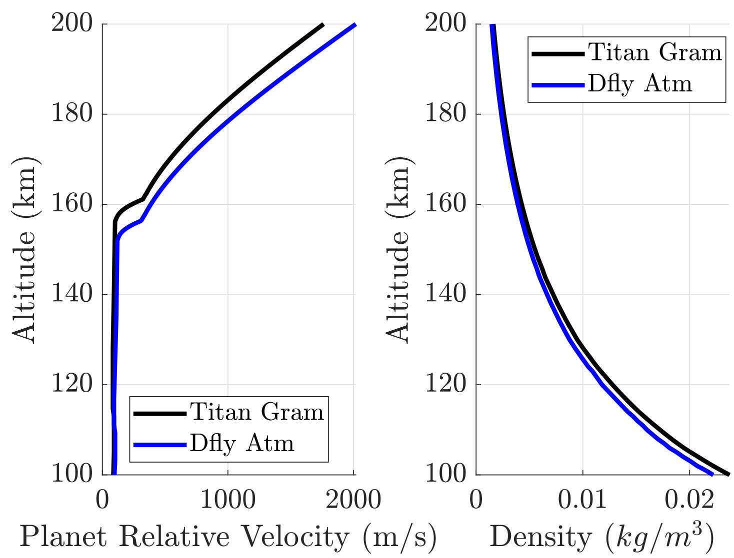


Fig. 16 Density and Planet Relative Velocity Correlation

The nadir, or off-vertical, angle is used to characterize the impact winds have on the probe's attitude. Fig 17 shows the nadir angle as a function of altitude. The results of the analysis includes two main areas of interest, one near 100 km and one near 70 km. Around 100 km, there is a peak in the simulation using the Dragonfly model that the Titan GRAM case does not experience. The more dramatic difference is between 60 and 70 km, with a notable jump in nadir angle. Tilt history recorded showed Huygens the largest instantaneous tilt recorded was 16 deg and it damped down to 5 deg [14]. As mentioned earlier, since the parachute is modeled as a simple drag force with a trim of 0 degrees, this behavior may be due to a lack of restoring moment that would be seen with a multi-body parachute model. However, this behavior was noted as an area to investigate for the Dragonfly EDL simulation.

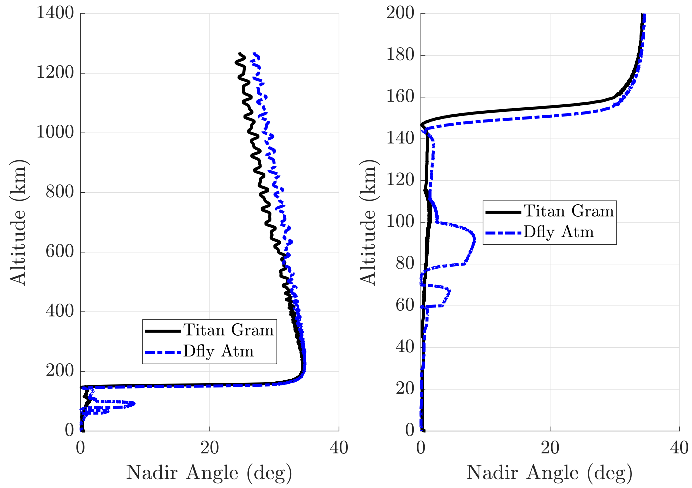


Fig. 17 Nadir Angle During the Trajectory

B. Dragonfly Atmosphere with Gusts

A gust model was used to compare results of the nominal trajectory, which has been shown to be in family with the flight data, and a trajectory using the current gusts used by the Dragonfly project. Fig. 18 show the comparison between the nominal winds and the nominal winds with the gust model added. The Dragonfly EDL gust model follows a 'random-walk' formalism similar to the one used for near-surface winds [19], but with altitude-dependent functions for the gust amplitude and length scale. A more detailed description of the Dragonfly gust model will be published in the future.

The variance in the zonal winds is shown in Figure 18, with peak differences between the two models reaching about 60m/s at the higher elevations. The right plot shows the comparison at lower altitudes. Meridional winds for both the nominal and gust cases are shown in Figure 18. Although the magnitudes throughout the trajectory are low, the presence of non-zero gusts and shifting directions are impactful to the dynamics of the vehicle. Similar to the meridional winds, the gusts provide variance and higher magnitude to the near-zero nominal wind profile for the vertical winds. The nadir angle, shown in Figure 19, highlights the large magnitude angles experienced when the gust model is introduced.

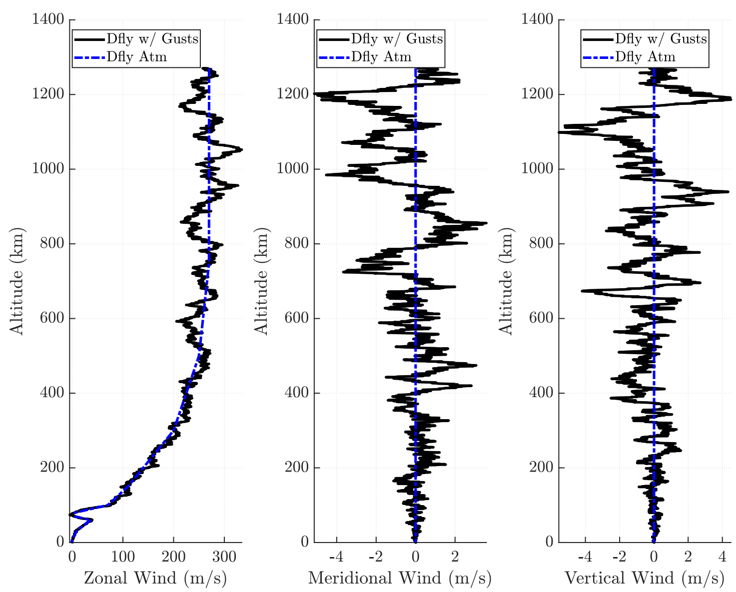


Fig. 18 Wind Comparison with the Addition of Gusts

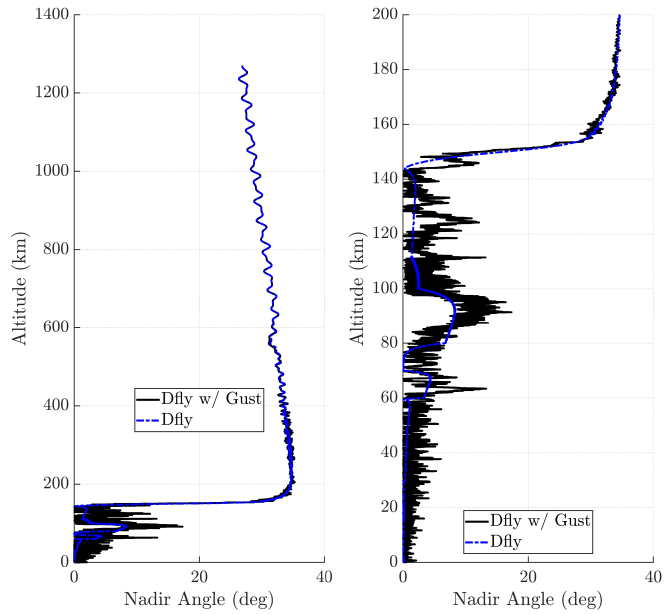


Fig. 19 Comparison of Nadir Angles with the Addition of Gusts

C. Landing Location with Dispersions

The Hugyens ground impact location was evaluated against the reconstructed results described in Ref. [20]. In that paper, published soon after the Huygens landing, combined reconstruction efforts from the Descent Trajectory Working Group (DTWG), Doppler Wind Experiment (DWE), and Descent Imager and Spectral Radiometer (DISR) to determined that the landing site was 10.3 ± 0.4 deg South in latitude and 167.7 ± 0.5 deg East in longitude. Although that final landing spot has been updated more recently [21], the current simulation utilizes initial states consistent with the assumptions used in analysis from immediately after the Huygens landing [11]. Fig. 20 shows the time history of the nominal trajectory and 99 percentile landing elipse using the Dragonfly atmosphere dispersions which bounds the estimated Huygens impact site.

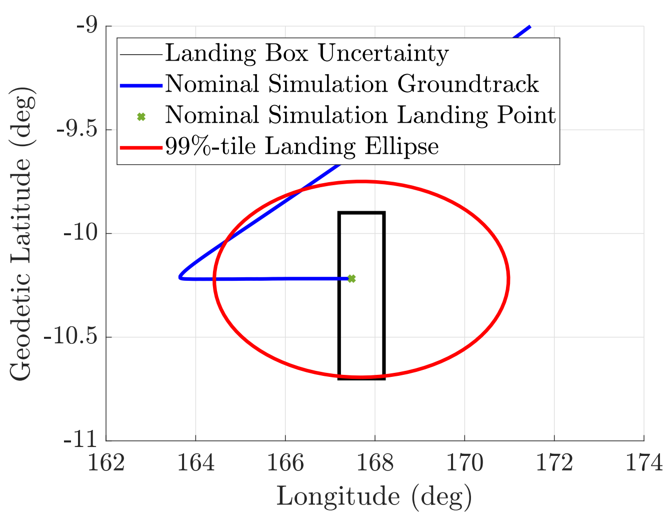


Fig. 20 Dragonfly Landing Ellipse Comparison

VI. Forward Work

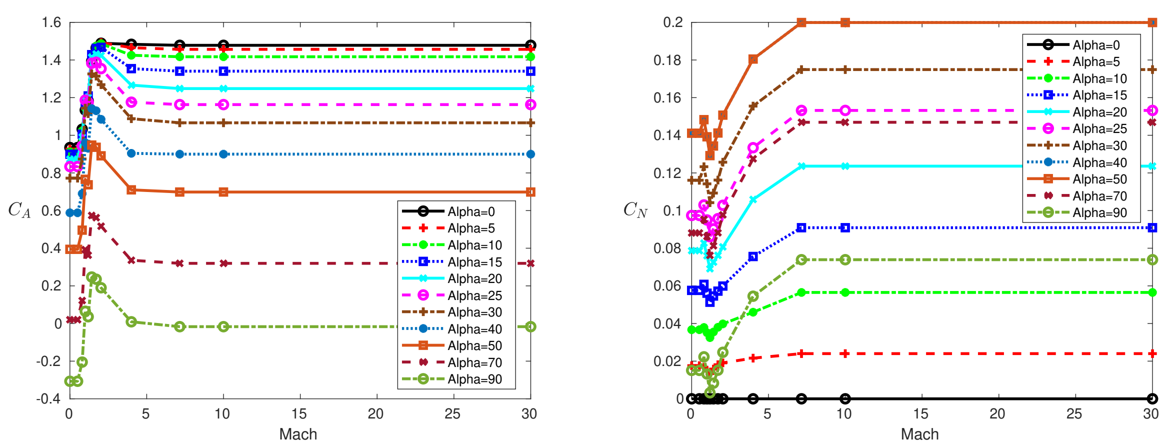
Preliminary assessment of the probe pitch and tilt angles and rates with respect to literature [14] showed a significantly over-damped system which led to the conclusion that the vehicle dynamics are not fully captured with a simple parachute model. The ongoing effort is to model the multi-body parachute to assess the attitude of the vehicle and how the atmosphere dispersions impact the probe. Furthermore, the dynamics shown in Fig. 17 have not been observed in the Dragonfly EDL simulation. As a result of this work, there will be an effort to go investigate this in the Dragonfly simulation to ensure there are no incorrect artificial dynamics being introduced with respect to how the model is implemented.

VII. Conclusion

A six degree of freedom EDL flight mechanics simulation has been developed to understand system performance for Dragonfly EDL. This simulation leverages several subsystem models, including the critical model of the Titan atmosphere. Over the last 20 years, a new atmosphere model has been built off of the data leveraged from multiple sources for Titan that is now being applied in the Dragonfly simulation. The data collected during the Huygens descent is invaluable for Dragonfly as the only mission that has collected in-situ data from Titan. The goal of this paper was to create a simulation that provided comparable results to the flight data available. The Dragonfly atmosphere could then be assessed to gain further insight into the most possible atmospheric conditions that the Huygens probe experienced during the EDL sequence. Though this work is ongoing, the results are in family with the flight data. As part of this effort it became clear the limitations of evaluating the attitude of the vehicle using a simple parachute model. Therefore, future work will include assessing the simulation using multi-body parachute model to evaluate against the reconstructed attitude data in literature. Finally, as part of this effort a secondary goal was set to compile the data used to generate these reference results in hope that it will facilitate others who wish to model Huygens descent.

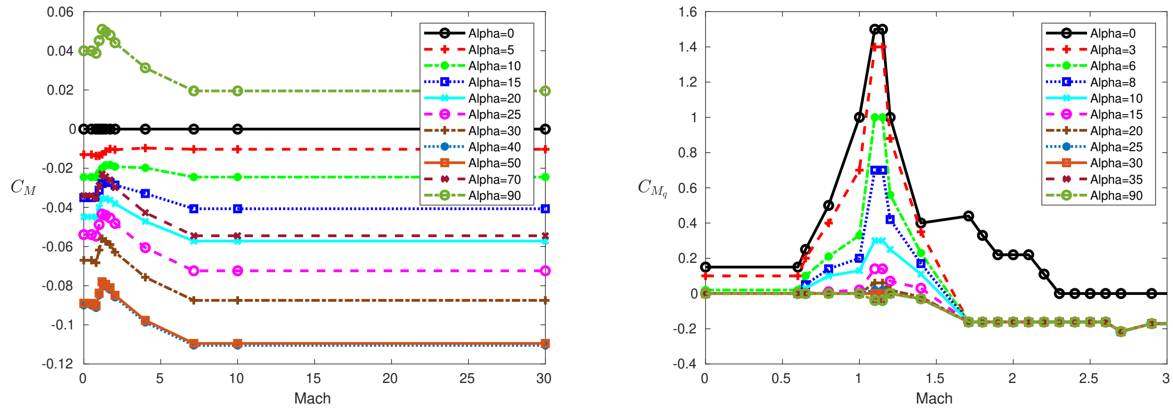
Appendix

A. Entry Module Aerodynamics



(a) C_A (b) C_N

Fig. 21 Axial and Normal Force Coefficients for the Entry Module

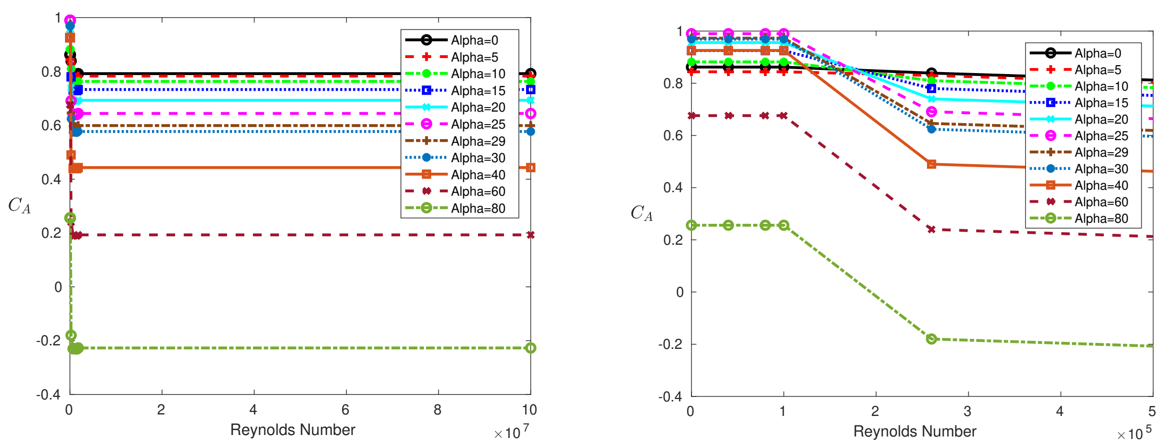


(a) C_M

(b) C_{M_q}

Fig. 22 Pitching Moment and Pitch Damping Coefficients for the Entry Module

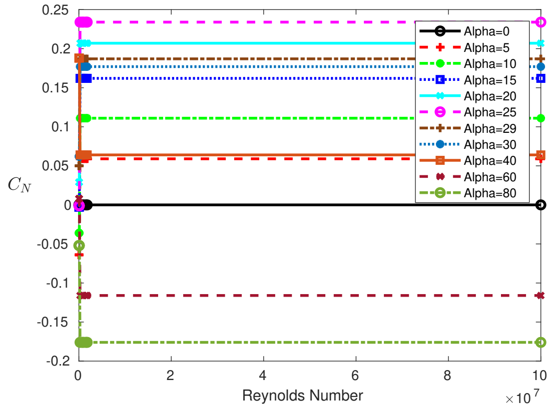
B. Probe Aerodynamics



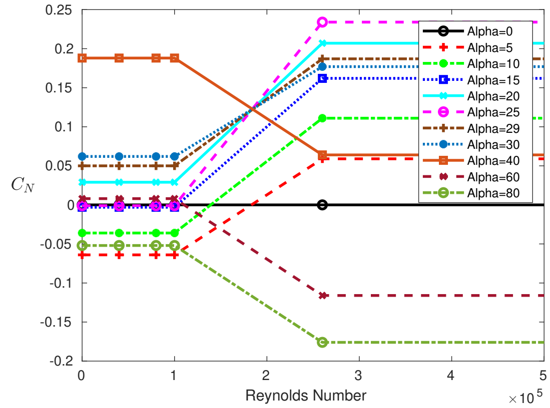
(a) C_A

(b) C_A Zoomed

Fig. 23 Axial Force Coefficients for the Probe

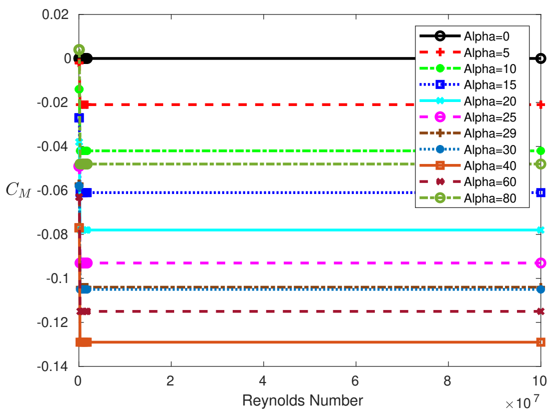


(a) C_N

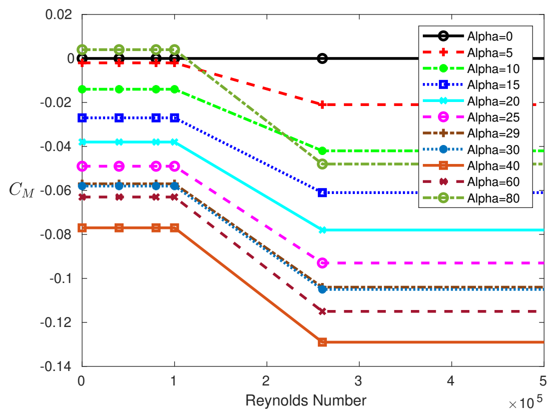


(b) C_N Zoomed

Fig. 24 Normal Force Coefficients for the Probe



(a) C_M



(b) C_M Zoomed

Fig. 25 Pitching Moment Coefficients for the Probe

Acknowledgments

The authors would like to the Dragonfly team who provided feedback for the development of the flight mechanics simulation.

References

[1] Lorenz, R. D., Turtle, E. P., Barnes, J. W., Trainer, M. G., Adams, D. S., Hibbard, K. E., Sheldon, C. Z., Zacny, K., Peplowski, P. N., Lawrence, D. J., et al., "Dragonfly: A rotorcraft lander concept for scientific exploration at Titan," *Johns Hopkins APL Technical Digest*, Vol. 34, No. 3, 2018, p. 14.

[2] Williams, R. A., Lugo, R. A., Marsh, S. M., Hoffman, J. A., Shidner, J. D., and Aguirre, J. T., "Enabling Thread Safety and Parallelism in the Program to Optimize Simulated Trajectories II," *AIAA SciTech 2023 Forum*, 2023, p. 0148.

[3] Winski, R. G., and Pensado, A. R., "Dragonfly Entry and Descent Flight Mechanics Modeling and Analysis," AIAA 2023-0601, *AIAA SciTech 2023,* National Harbor, MD, 2023.

[4] Lorenz, R. D., "Dragonfly : Entry and Descent one Titan Year after Huygens," AIAA 2023-0599*, AIAA SciTech 2023,* National Harbor, MD, 2023.

[5] MSFC, "TitanGRAM," , 2004. URL https://software.nasa.gov/software/MFS-32297-1#:~:text=Titan-GRAM%20is%20a%20Fortran-based%20program%20that%20provides%20engineering,temperature%2C%20pressure%2C%20and%20winds%20for%20the%20Titan%20atmosphere.

[6] Lorenz, R. D., Newman, C. E., Tokano, T., Mitchell, J. L., Charnay, B., Lebonnois, S., and Achterberg, R. K., "Formulation of a wind specification for Titan late polar summer exploration," *Planetary and Space Science*, Vol. 70, No. 1, 2012, pp. 73–83.

[7] Kazeminejad, B., Atkinson, D. H., Pérez-Ayúcar, M., Lebreton, J.-P., and Sollazzo, C., "Huygens' entry and descent through Titan's atmosphere—Methodology and results of the trajectory reconstruction," *Planetary and Space Science*, Vol. 55, No. 13, 2007, pp. 1845–1876.

[8] Justus, C., Duvall, A., and Kller, V. W., "Engineering-level model atmospheres for Titan and Mars," *Planetary probe atmospheric entry and descent trajectory analysis and science*, Vol. 544, 2004, pp. 311–316.

[9] Lebonnois, S., Burgalat, J., Rannou, P., and Charnay, B., "Titan global climate model: A new 3-dimensional version of the IPSL Titan GCM," *Icarus*, Vol. 218, No. 1, 2012, pp. 707–722. https://doi.org/10.1016/j.icarus.2011.11.032, URL https://www.sciencedirect.com/science/article/pii/S0019103511004593.

[10] Powell, R. W., Lockwood, M. K., Cruz, J. R., Striepe, S. A., Sutton, K., Fisher, J., Takashima, N. T., Justus, J., Keller, V. W., Bose, D., et al., "Cassini/Huygens Probe Entry, Descent, and Landing (EDL) at Titan Independent Technical Assessment," Tech. rep., 2009.

[11] Striepe, S. A., Blanchard, R. C., Kirsch, M. F., and Fowler, W. T., "Huygens Titan probe trajectory reconstruction using traditional methods and the program to optimize simulated trajectories II," *17th AAS/AIAA Space Flight Mechanics Meeting*, 2007.

[12] Pensado, A. R., Winski, R. G., Williams, J., and Robb, C., "Dragonfly Mission Entry and Descent Modeling and Simulation Overview," *AIAA SciTech 2025,* Orlando, FL, 2025.

[13] Lebleu, D., "Huygens Probe/Probe Reference Data for Post Flight Analysis," Tech. rep., 2005.

[14] Lorenz, R. D., "Decoding the Descent Dynamics of the Huygens Probe," *2022 IEEE Aerospace Conference (AERO)*, IEEE, 2022, pp. 1–14.

[15] Schipper, A., "Huygens Aerodynamic Databases Status Summary," Tech. rep., 2004.

[16] Huber, L., "NASA Planetary Data System - Huygens Database," , 2006. URL https://atmos.nmsu.edu/PDS/data/PDS4/Huygens/hphk_bundle/DOCUMENT/.

[17] Lorenz, R. D., Lebreton, J.-P., Leroy, A., and Pérez-Ayúcar, M., "Evolution of the Huygens Probe Spin During Parachute Descent," *Journal of Spacecraft and Rockets*, Vol. 58, No. 3, 2021, pp. 609–618.

[18] Lebreton, J.-P., and Leroy, A., "Huygens Close-out Activities Final Technical Report," Tech. rep., 2020.

[19] Lorenz, R. D., "Turbulence for extraterrestrial aviation: Gust specification for Dragonfly's powered flights," *Planetary and Space Science*, Vol. 214, 2022, p. 105459.

[20] Lebreton, J.-P., Witasse, O., Sollazzo, C., Blancquaert, T., Couzin, P., Schipper, A.-M., Jones, J. B., Matson, D. L., Gurvits, L. I., Atkinson, D. H., Kazeminejad, B., and Pérez-Ayúcar, M., "An overview of the descent and landing of the Huygens probe on Titan," *Nature*, Vol. 438, No. 7069, 2005, pp. 758–764. https://doi.org/10.1038/nature04347, URL https://www.nature.com/articles/nature04347, publisher: Nature Publishing Group.

[21] Kazeminejad, B., Atkinson, D. H., and Lebreton, J.-P., "Titan's new pole: Implications for the Huygens entry and descent trajectory and landing coordinates," *Advances in Space Research*, Vol. 47, No. 9, 2011, pp. 1622–1632.