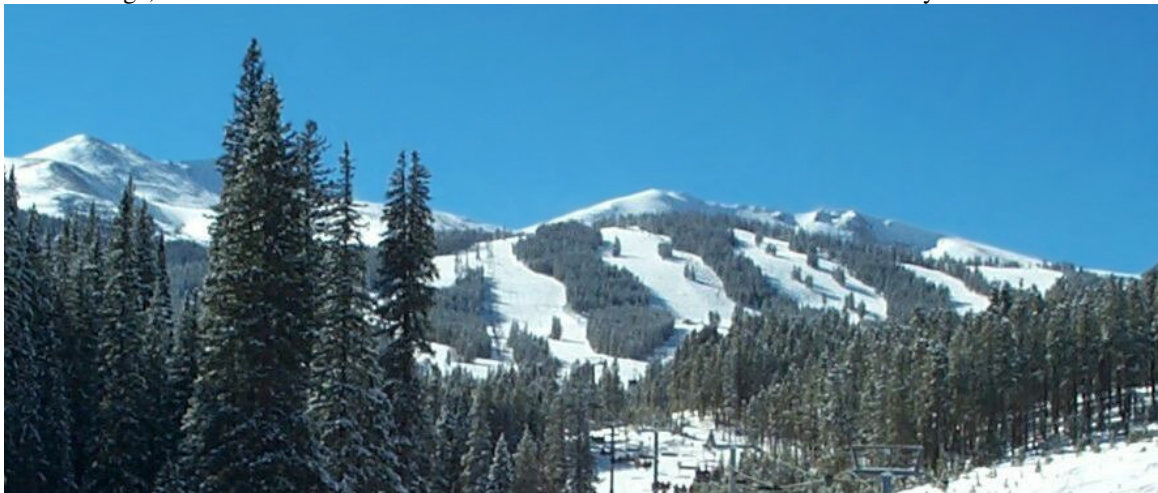# TITAN EXPLORER ENTRY, DESCENT AND LANDING TRAJECTORY DESIGN

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29th ANNUAL AAS GUIDANCE AND CONTROL CONFERENCE

TITAN EXPLORER ENTRY, DESCENT AND LANDING TRAJECTORY DESIGN

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The Titan Explorer mission concept includes an orbiter, entry probe and inflatable airship designed to take remote and in-situ measurements of Titan's atmosphere. A modified entry, descent and landing trajectory at Titan that incorporates mid-air airship inflation (under a parachute) and separation is developed and examined for Titan Explorer. The feasibility of mid-air inflation and deployment of an airship under a parachute is determined by implementing and validating an airship buoyancy and inflation model in the trajectory simulation program, Program to Optimize Simulated Trajectories II (POST2). A nominal POST2 trajectory simulation case study is generated which examines different descent scenarios by varying airship inflation duration, orientation, and separation. The buoyancy model incorporation into POST2 is new to the software and may be used in future trajectory simulations. Each case from the nominal POST2 trajectory case study simulates a successful separation between the parachute and airship systems with sufficient velocity change as to alter their paths to avoid collision throughout their descent. The airship and heatshield also separate acceptably with a minimum distance of separation from the parachute system of 1.5 km. This analysis shows the feasibility of airship inflation on a parachute for different orientations, airship separation at various inflation times, and preparation for level-flight at Titan.

INTRODUCTION

The National Aeronautics and Space Administration's (NASA) scientific and exploration efforts strive to accomplish two strategic goals: 1) to explore the fundamental principles of physics, chemistry, and biology through research in the unique natural laboratory of space, and 2) to explore the solar system and the universe beyond, understand the origin and evolution of life, and search for evidence of life elsewhere.[1] To help achieve the latter of these goals, many mission concepts are on the drawing board to provide a more affordable way of delivering spacecraft and scientific instruments to their planetary destinations. One of these mission concepts is Titan Explorer. Titan, the largest moon of Saturn, is currently the only known moon in the solar system to have an atmosphere. Additionally, the condition of Titan's atmosphere (rich in nitrogen and hydrocarbons, similar to Earth in its pre-biotic state) may give clues about the origin of life on Earth. Due to the expensive (billions of US dollars) and lengthy flight (6-11 years) it takes to reach the

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Saturnian system,[2] cost and time saving technologies such as propellant-saving maneuvers and atmospheric-entry techniques, must be developed and utilized to enable a feasible mission to Titan.

Entry, descent and landing (EDL) is a mission sequence consisting of three main stages that involve a vehicle entering an atmosphere, descending through the atmosphere with the aid of one or many parachutes or other decelerators, and either landing on the surface of the planet or transitioning into other atmospheric flight operations. Through the use of an atmosphere via aerodynamic forces to modify a trajectory, this direct entry technique is important for enabling exploration and scientific in-situ measurement of planetary atmospheres and surfaces. Various EDL methods have been successfully utilized in many NASA missions to date. In addition, the European Space Agency (ESA) Huygens probe (the first probe to enter Titan's atmosphere and impact its surface) used EDL techniques such as ballistic entry with a three-stage parachute descent system, to successfully take in-situ and scientific measurements at Titan. However, NASA's Titan Explorer[3,4] mission concept incorporates airship flight for additional scientific measurements and it may also give insight into a more globalized perspective of Titan's atmosphere and surface characteristics. The buoyancy, inflation and transition of the airship, in addition to the entry and descent, must be modeled to analyze the feasibility of mid-air airship inflation (under a parachute) and deployment.

TRAJECTORY DESIGN AND SIMULATION

The Titan Explorer EDL trajectory development begins with the 3-degree-of-freedom (3DOF) entry trajectory simulation in Program to Optimize Simulated Trajectories II (POST2).[5,6,7] POST2 is a generalized point mass, discrete parameter targeting and optimization trajectory program. POST2 has the ability to simulate 3DOF, 6DOF and multi-DOF trajectories for multiple vehicles in various flight regimes (i.e. entry, launch, rendezvous, and intercept trajectories). POST2 also has the capability to include different atmosphere, aerodynamics, gravity, propulsion, parachute and navigation system models. Many of these models have been used to simulate the entry trajectories for previous NASA missions, i.e. Mars Exploration Rovers (MER), Genesis, Stardust, Mars Path Finder (MPF), as well as current and planned NASA missions such as Mars Phoenix Lander, and Mars Science Laboratory.

The Titan Explorer EDL simulation includes vehicle geometric parameters, an aerodynamic database, Titan's gravity and atmosphere models, and initial states. Titan Global Reference Atmospheric Model (Titan-GRAM), parachute inflation and drag models are also included in the simulation. Table 1 shows the main sequential events in the POST2 simulation with commentary. It should be noted that the simulation event numbers are widely spaced to account for the possibility of future event additions to the simulation.

Table 1
TITAN EXPLORER NOMINAL POST2 SIMULATION EVENTS

Event	Event Description	Comment
1	Simulation initialization	Input vehicle geometry, mass, initial conditions, and gravity model
100	Entry interface and aerodynamic activation	Activate atmosphere model
200	Parachute activation	Start parachute timers
220	Parachute deployment	
240	Parachute inflation	Parachute full inflation
300	Backshell-heatshield separation and airship inflation	Initialize airship inflation
350	Parachute-backshell and airship-heatshield separation	
350	Multiple vehicle tracking activation	Simulate separated vehicles/systems
375	Heatshield deployment	
400	Initial airship level-flight	Fully-inflated airship reaches final altitude
450	Parachute-backshell surface touchdown	
999	Final event	Simulation cut-off after Event 450

Critical Design Requirements

The initial conditions for the Titan Explorer entry phase of the probe consist of a ballistic direct entry from a hyperbolic approach with an inertial entry velocity and altitude of 6.5 km/s and 1000 km.[8] The entry altitude of 1000 km is a commonly assumed atmospheric interface altitude for Titan. The entry flight path angle (EFPA) requirement of -50° with ±5° (3σ) dispersions from R. J. Haw[8] lies within the determined skip-out EFPA and Huygens reference trajectory nominal EFPA range of -43.5° and -64°. A minimum duration of 20 minutes on the parachute was selected to give adequate margin for airship inflation and airship preparation for separation. The heatshield is deployed only after airship separation from the parachute. The entry aeroshell is assumed to have a diameter of 3.75 m and 70-degree sphere-cone forebody geometry.[3,4]

Airship Inflation and Deployment Approach

We have made certain simplifying assumptions in developing a buoyancy and inflation model for the Titan Explorer airship during its descent on the parachute. The mass flow rate of the airship lifting gas is undetermined from a systems perspective and is assumed to be constant from the inflation tank to the gasbag, making the growth of the inflation gas mass linear during inflation. A constant mass flow rate may be achieved by keeping the gas pressure and temperature constant. A pressure regulator can be used to keep the pressure constant, and it is assumed that the tank temperature can be held constant through radiative heating if the mass flow rate is slow enough. Airship orientation on the heatshield is considered two different ways: nose-forward attached to heatshield (airship length parallel to flow) or gondola attached to heatshield (airship length perpendicular to flow). During inflation of the airship, the nose-attached orientation is a more streamlined approach. The gondola-attached orientation may be more dynamically stable, but exhibit more drag. Figure 1 shows the two possible orientations for the airship.
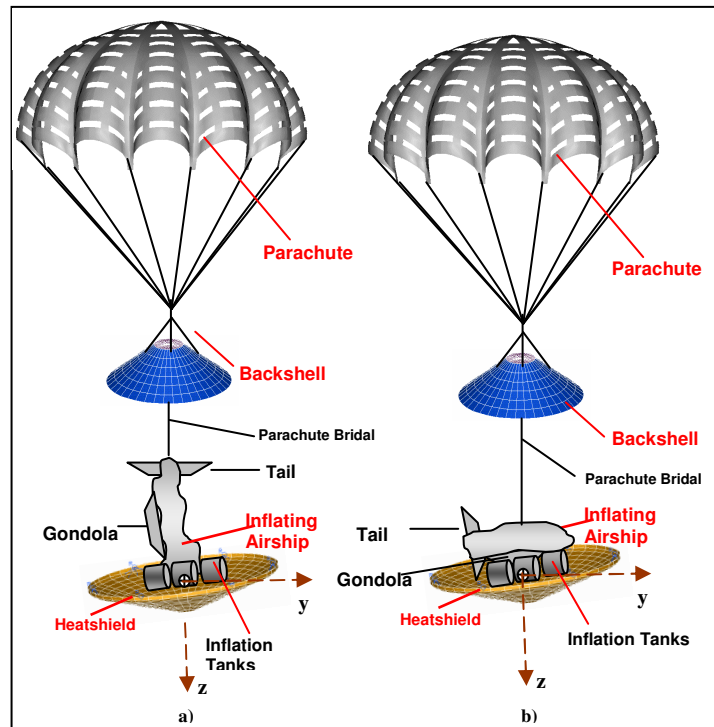

Figure 1. Airship Orientation (not to scale): a) Nose-Attached b) Gondola-Attached

Parachute Descent System Design

The Titan Explorer parachute descent subsystem is chosen as a 20° conical ribbon parachute, a mortar, and system support. The parachute is sized to meet two criteria: 1) a descent time between one to two hours for airship inflation process, and 2) the ballistic coefficient of the heatshield-airship combination during inflation is greater than 1.4 times that of the parachute-backshell combination.[9] The latter criterion is a rule of thumb used in industry to determine a feasible separation of two components during flight. Using these criteria, we designed the parachute to a 5.75 m nominal diameter, corresponding to a nominal area of 25.95 m^2 and drag area of 13.62 m^2. Additionally, to meet the descent time criterion between one to two hours, we chose a deployment Mach number of 1.1. Higher deployment Mach numbers would extend the descent time. Delaying parachute deployment until this Mach number is a conservative approach in that it further delays the start of the descent phase such that descent begins much closer to the surface.

Airship Buoyancy and Inflation Model

The buoyancy and inflation model of the airship at Titan is developed to estimate buoyancy, inflation rates, airship growth during inflation, and ballistic coefficients. The model is implemented into POST2 and integrated with the equations of motion to calculate the nominal trajectory needed to simulate and analyze the trajectory of the airship during inflation while attached to the parachute, and the airship separation from the parachute and heatshield.

The buoyancy and inflation model utilizes the Archimedes principle of buoyancy, linear inflation rates, and atmospheric, entry probe and parachute conditions (i.e. density, pressure, temperature, altitude, and velocity). Buoyancy is determined from the volume of the airship gasbag and the density of the helium lifting gas.[10,11,12] The buoyant lift of the airship[12] (L_a) at Titan is calculated from the buoyant mass (B) or total displaced mass of the gasbag, the surface gravitational force at Titan (g_{titan}), the volume of the gasbag (V_{gb}), and the difference between the atmospheric density (ρ_{atm}) and the density of helium (ρ_{He}) using the equation

$$L_a = B\, g_{titan} = V_{gb}\,(\rho_{atm} - \rho_{He})\, g_{titan} \tag{1}$$

V_{gb} is determined by the lifting gas mass and density at a buoyant altitude (airship operational altitude) of 5 km above the Titan surface. The gasbag half-length and maximum radius are assumed to be 8.42 m and 1.68 m, respectively.[3] From those values and the lifting gas mass, inflation is modeled such that the lifting gas mass flow rate was held constant and the growth of the gasbag radius is assumed to be linear with respect to time. Two different inflation durations were tested: 20 minutes and 10 minutes. Figure 2 shows the linear growth of airship buoyant lift with respect to inflation percentage generated in POST2.
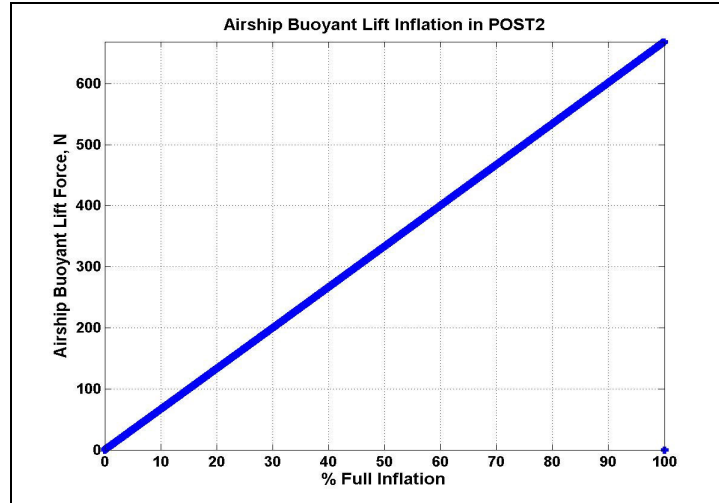

Figure 2. POST2 Airship Buoyant Lift during Inflation

After full airship inflation, L_a remains constant at 667.4 N with a V_{gb} of 144.5 m^3. These full inflation conditions were selected to achieve a buoyant altitude (airship operational altitude) of 5 km. The completion of airship inflation had been designed for an altitude range of 8 km to 6 km (close to, but above, the airship operational altitude) to give a margin before heatshield deployment for airship orientation and system configuration. Hence, the inflation-initialization altitude depends on the inflation duration and inflation-completion altitude. The airship inflation-initialization altitudes were then chosen as 15 km for a 20 minute inflation duration, and 11 km for a 10 minute inflation duration.

To determine the feasibility of airship inflation and separation with the parachute, two parameters are taken into consideration: aerodynamic drag (D) and ballistic coefficient (BC). The difference in aerodynamic drag of the parachute and the inflating airship-heatshield combination determines whether the tether between the airship-heatshield and parachute is taut (i.e. whether there is tether tension).[13] As the airship buoyancy increases, the tension between the two systems decreases and the drag force transmitted to the parachute also decreases, which leads to a less effective parachute. An effective design therefore seeks to achieve a drag force of the parachute that must always be greater than the airship-heatshield combination drag force. Figure 3 illustrates the effects of airship buoyancy growth on the parachute during descent.
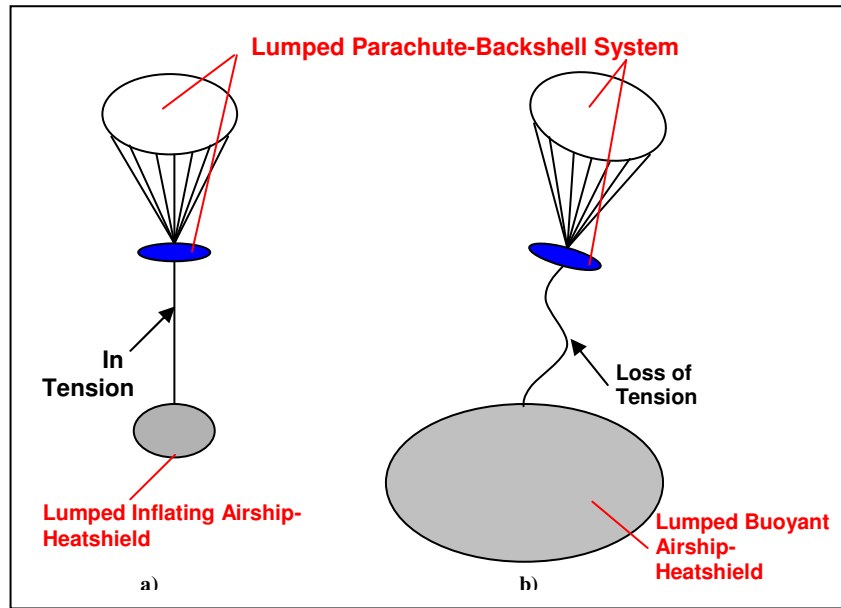

Figure 3. Schematic of Airship Buoyancy Effects during Descent (not to scale)

A mismatch or percentage difference in ballistic coefficient of the parachute-backshell combination and the airship-heatshield combination is used to determine the feasibility of separation of the parachute-backshell and airship-heatshield combination. The rule of thumb used for a feasible separation is: the ballistic coefficient of the airship-heatshield combination must be greater than the nominal ballistic coefficient of the parachute-backshell combination by 40%, including dispersions.[9] Figure 4 illustrates the free-body diagram of the airship-heatshield system used to determine the appropriate ballistic coefficient equation.
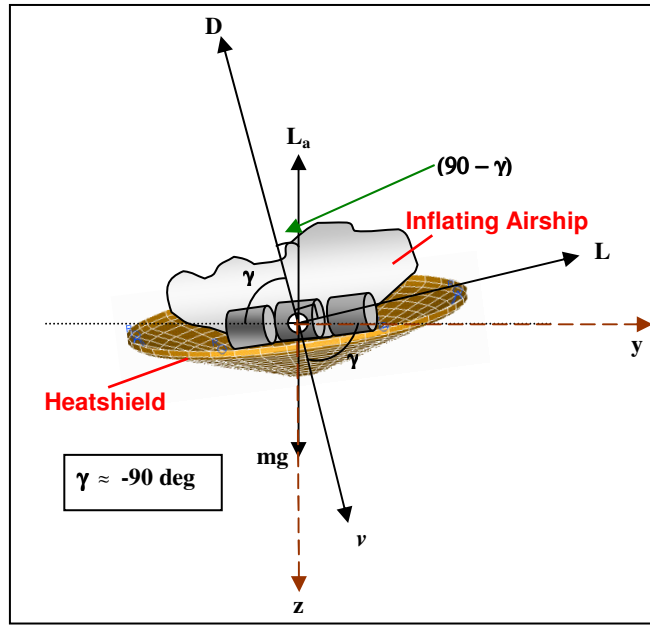
Figure 4. Airship-Heatshield Free-Body Diagram

To calculate the ballistic coefficient with the inclusion of buoyant mass for the airship-heatshield combination (BC_{hs}), the buoyant mass (B) is subtracted from the airship-heatshield combination mass (m_{hs}) to account for buoyancy effects and the equation is multiplied by the dynamic pressure (q) to acquire the airship-heatshield combination drag (D_{hs}) in the denominator. The ballistic coefficient of the parachute-backshell combination (BC_{bs}) is the mass of the system (m_{bs}) divided by the drag coefficient of the parachute (C_{Dp}) multiplied by the nominal parachute area (S_o). The calculation of the ballistic coefficient of each system (with the incorporation of buoyancy and its components) are determined by

$$BC_{hs} = \frac{m_{hs} - B}{C_{Dhs} A_{eff}} = \frac{q\,(m_{hs} - B)}{q\,C_{Dhs} A_{eff}} = \frac{q\,(m_{hs} - B)}{D_{hs}} \tag{2}$$

and

$$BC_{bs} = \frac{m_{bs}}{C_{Dp} S_o}. \tag{3}$$

Using these BC values for each system, the ballistic coefficient mismatch is calculated by

$$\Delta BC = \left(\frac{BC_{hs} - BC_{bs}}{BC_{hs}} \right). \tag{4}$$

The effective area (A_{eff}) for the BC_{hs} is the cross-sectional area of the system perpendicular to the flow. The determination of A_{eff} is based on either a gondola-attached or nose-attached orientation of the airship on the heatshield. A_{eff} during inflation increases, for the gondola-attached orientation, and at approximately 62.5% the cross-sectional area of the airship overtakes that of the heatshield. Figure 5 presents the change in A_{eff} with inflation percentage for the gondola-attached orientation, which is the same for both inflation durations of 10 and 20 minutes.
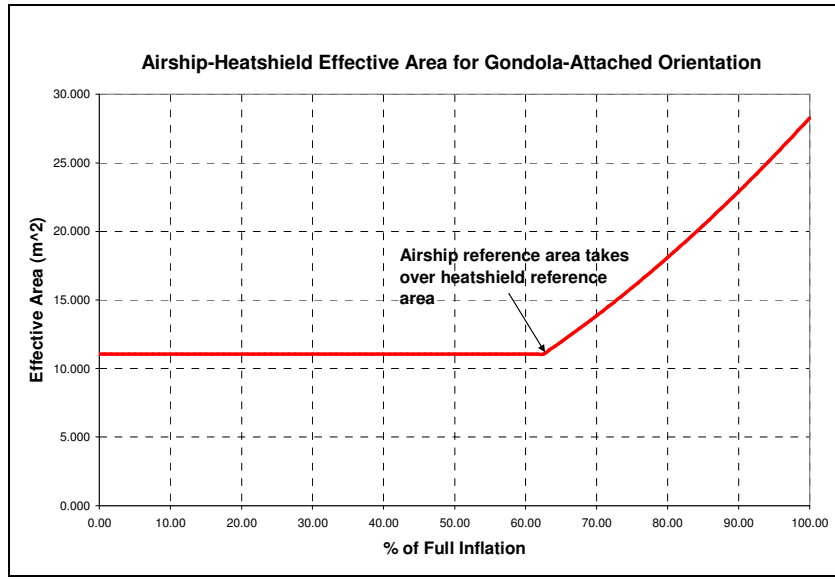
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Figure 5. Heatshield-Airship System A_{eff} for Gondola-Attached Orientation

For the nose-attached orientation of the airship, the heatshield cross-sectional area is always greater than the airship, even at full inflation. Therefore, A_{eff} in that case is always equal to the reference area of the heatshield, that is, it remains constant throughout the simulation.

Nominal 3DOF Trajectory Case Study

A nominal 3DOF POST2 trajectory case study was conducted varying only inflation duration, airship orientation, and separation time. The study was broken down into six simulated trajectory cases as shown in Table 2. The first two cases simulate the nose-attached orientation of the airship, which has a constant A_{eff} equal to the reference area of the heatshield, producing no additional aerodynamic drag for the airship-heatshield system. Therefore, airship separation in both cases is initiated at 100% inflation. The next four cases simulate the gondola-attached airship orientation, which has an A_{eff} that grows linearly with gasbag inflation, producing additional aerodynamic drag for the airship-heatshield system. Due to the additional drag produced by the growth in airship A_{eff} for the gondola-attached orientation, the trajectory for parachute-airship separation at 100% inflation was not simulated.

Table 2
NOMINAL 3DOF POST2 TRAJECTORY CASE STUDY

Case No.	Airship Orientation	Airship Inflation	Airship Separation	Event Altitude Selection
1	Nose-attached	20 minutes	100% inflation	▪ 15 km inflation initialization altitude ▪ 5.6 km heatshield deployment altitude
2	Nose-attached	10 minutes	100% inflation	▪ 11 km inflation initialization altitude ▪ 5.6 km heatshield deployment altitude
3	Gondola-attached	20 minutes	40% inflation	▪ 15 km inflation initialization altitude ▪ 5.25 km heatshield deployment altitude
4	Gondola-attached	20 minutes	60% inflation	▪ 15 km inflation initialization altitude ▪ 5.25 km heatshield deployment altitude
5	Gondola-attached	10 minutes	40% inflation	▪ 11 km inflation initialization altitude ▪ 5.25 km heatshield deployment altitude
6	Gondola-attached	10 minutes	60% inflation	▪ 11 km inflation initialization altitude ▪ 5.25 km heatshield deployment altitude

TRAJECTORY SIMULATION RESULTS

Entry, Descent and Airship Transition Timeline

The entry, descent and airship transition timeline gives an overview of the results of the nominal 3DOF POST2 simulation output. The sequence begins with probe entry interface, followed by parachute deployment and descent. We assume airship inflation initiation at the time of backshell and heatshield separation, and descent of the airship-heatshield on the parachute bridle. The airship is then cut away from the parachute-backshell system at some point in inflation (i.e. 40%, 60%, or 100%) and the heatshield is released from the fully-inflated airship before it reaches a 5 km altitude. The completion of the entry, descent and airship transition establishes the initial conditions for mission operations of the airship at its operational altitude. Figure 6 illustrates the nominal Titan Explorer entry, descent and airship transition timeline generated from the nominal 3DOF POST2 simulation output. The range of values for time height, and velocity at each event in the timeline, starting at airship inflation initialization, covers each of the six cases of the nominal descent trajectory case study.
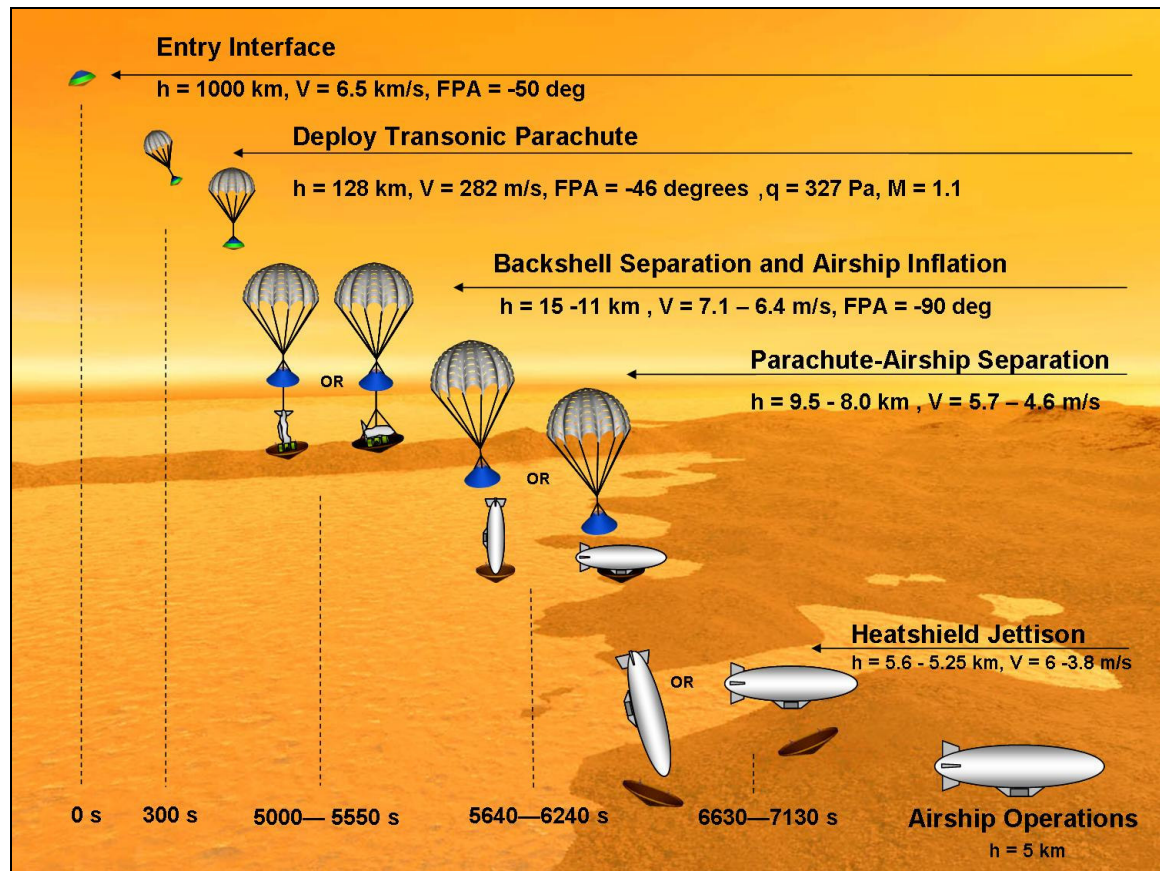

Entry Interface
h = 1000 km, V = 6.5 km/s, FPA = -50 deg

Deploy Transonic Parachute
h = 128 km, V = 282 m/s, FPA = -46 degrees , q = 327 Pa, M = 1.1

Backshell Separation and Airship Inflation
h = 15 -11 km , V = 7.1 – 6.4 m/s, FPA = -90 deg

Parachute-Airship Separation
h = 9.5 - 8.0 km , V = 5.7 – 4.6 m/s

OR

OR

OR

Heatshield Jettison
h = 5.6 - 5.25 km, V = 6 -3.8 m/s

0 s   300 s   5000— 5550 s   5640—6240 s   6630—7130 s   **Airship Operations**
h = 5 km

Figure 6. Titan Explorer Nominal EDL Timeline

Airship/Parachute Inflation and Separation Feasibility

The difference in aerodynamic drag of the parachute-backshell and airship-heatshield combination was calculated to determine the maximum point at which the parachute and airship system could be separated. The aerodynamic drag of the parachute was taken from the nominal POST2 3DOF simulation, tabulated, and compared to the drag of the airship taken from the inflation and buoyancy model for both gondola-attached and nose-attached orientations. For the nose-attached orientation of the airship, the reference area, A_{eff}, of the

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airship never exceeds that of the heatshield. Therefore, the airship-heatshield aerodynamic drag has variation only due to the change in dynamic pressure during inflation and is always less than the parachute drag, even at 100% airship inflation. The comparison of the parachute drag and airship-heatshield drag is illustrated in Figure 7.
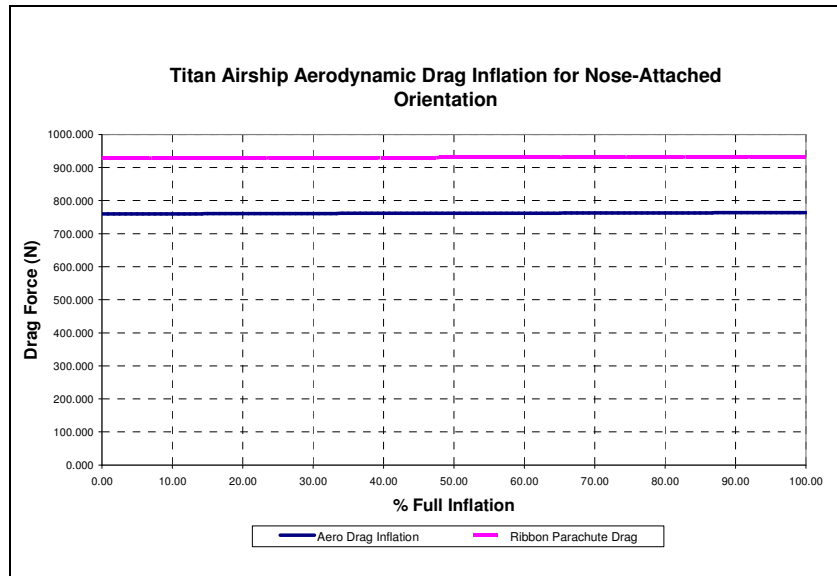

Figure 7. Aerodynamic Drag Comparison for Nose-Attached Airship Orientation

For the gondola-attached orientation of the airship, A_{eff} of the airship exceeds that of the heatshield at about 62.5% inflation. The airship-heatshield aerodynamic drag begins to overtake the parachute drag at 69.2% inflation, indicating that the parachute and airship should be separated before this point. Figure 8 shows the comparison of the parachute drag and airship-heatshield drag for the gondola-attached orientation.
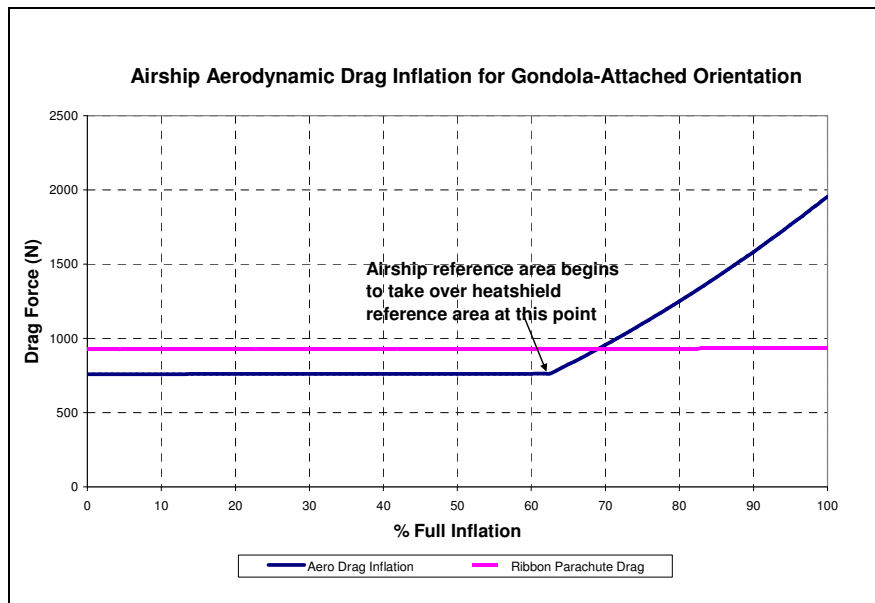

Figure 8. Aerodynamic Drag Comparison for Gondola-Attached Airship Orientation

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The airship and parachute separation feasibility was determined by the difference in BC of the parachute-backshell and airship-heatshield systems. For the gondola-attached airship orientation, a BC mismatch of 88.7% for separation at 40% inflation was calculated, which is substantially above the recommended 40% mismatch for a heatshield separation from an entry body while on the parachute. Also, for separation at 60% inflation the BC mismatch was 87.0%, which is well above the recommended mismatch. For the nose-attached airship orientation, the BC mismatch for separation at 40% and 60% inflation is equal to that of the gondola-attached orientation because A_{eff} does not exceeded the reference area of the heatshield at those percentages for both orientations (see Figure 7 and Figure 8). A BC mismatch of 81.9%, for the nose-attached orientation, was calculated for separation at 100% inflation. For the gondola-attached orientation, the additional drag produced by the growth in A_{eff} (see Figure 8) for inflation above 60% leads to an ineffective parachute as illustrated in Figure 3. For this reason, the BC mismatch for the gondola-orientation was not calculated for separation at 100% inflation. Based on the inflation model, the BC mismatch calculation is invariant for different inflation durations. Separation of the airship-heatshield from the parachute system for either airship orientation is feasible at 40% and 60% inflation. Airship separation at 100% inflation is feasible for the nose-attached orientation only. Significant additional margin is available by separating the airship-heatshield from the parachute system prior to full airship inflation.

Nominal Trajectory Case Study Summary

The six nominal 3DOF trajectory cases were examined by plotting each descent altitude profile, and then determining separation in altitude between the parachute and airship at heatshield deployment. All six cases simulated successful airship inflation under the parachute, separation from the parachute, and heatshield deployment. Even though all cases were feasible in terms of airship inflation and separation, there was a most and least desirable case. Desirability was based on the altitude of separation between the airship and parachute at heatshield deployment and time available to maneuver the airship before the airship and parachute reach a common altitude after heatshield deployment.

Case 2 (with a nose-attached airship orientation, 10 minute airship inflation duration, and airship separation at 100% inflation) was feasible and the least desirable. Figure 9 shows the descent of the airship during inflation, separation from the parachute, and heatshield deployment. Backshell separation and airship inflation occurs at the selected altitude of 11 km and velocity of 6.4 m/s. The simulation data predicts a successful separation shown by the large increase in velocity of the airship-heatshield combination, which is more massive with less drag, and large decrease in velocity of the parachute-backshell combination, which is less massive with more drag. This change in velocity occurs almost instantaneously after separation. The heatshield is deployed from the airship and descends to the surface, while the airship descends to its buoyant altitude of 5 km.
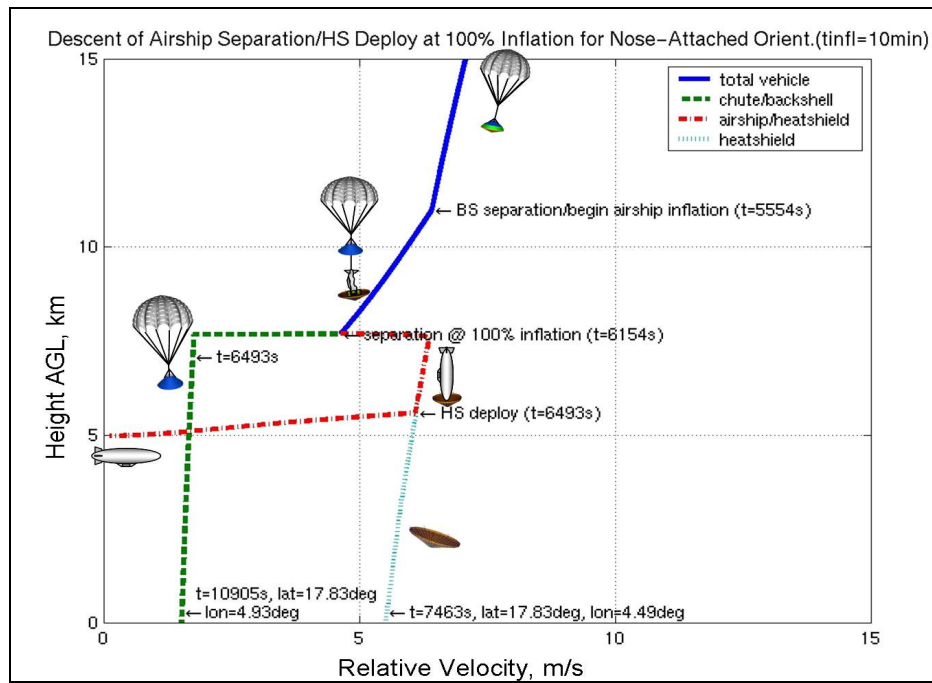
Figure 9. Case 2 3DOF POST2 Descent Trajectory

Figure 10 is the altitude profile for Case 2. It shows the gradual descent of the parachute-backshell, deployment of the heatshield and initial level flight of the airship. The separation in altitude between the two systems at heatshield deployment is 1.5 km and the time between heatshield deployment and airship-parachute common altitude is 19 minutes.
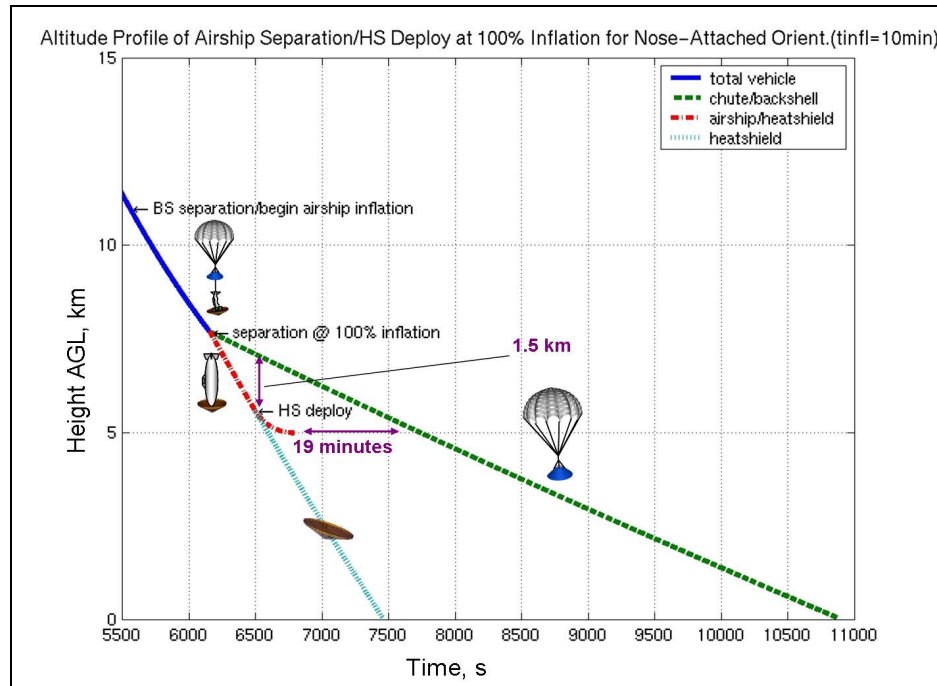

Figure 10. Case 2 3DOF POST2 Altitude Profile

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Case 3 (with a gondola-attached airship orientation, 20 minute airship inflation duration, and airship separation at 40% inflation) was feasible and the most desirable. Figure 11 shows the descent of the airship during inflation, separation from the parachute, and heatshield deployment. The descent profile of Case 3 is different than Case 2 in that the airship separates at 40% inflation and A_{eff} grows during inflation because of the gondola-attached orientation of the airship. The first change in slope of the airship-heatshield descent occurs when the effective area overtakes that of the heatshield reference area. The second change in slope occurs when the airship is fully inflated and there is no more change in buoyant force reducing the deceleration rate. There is also a large change in velocity at heatshield deployment because of the loss of the drag of the inflated airship attached to the heatshield.
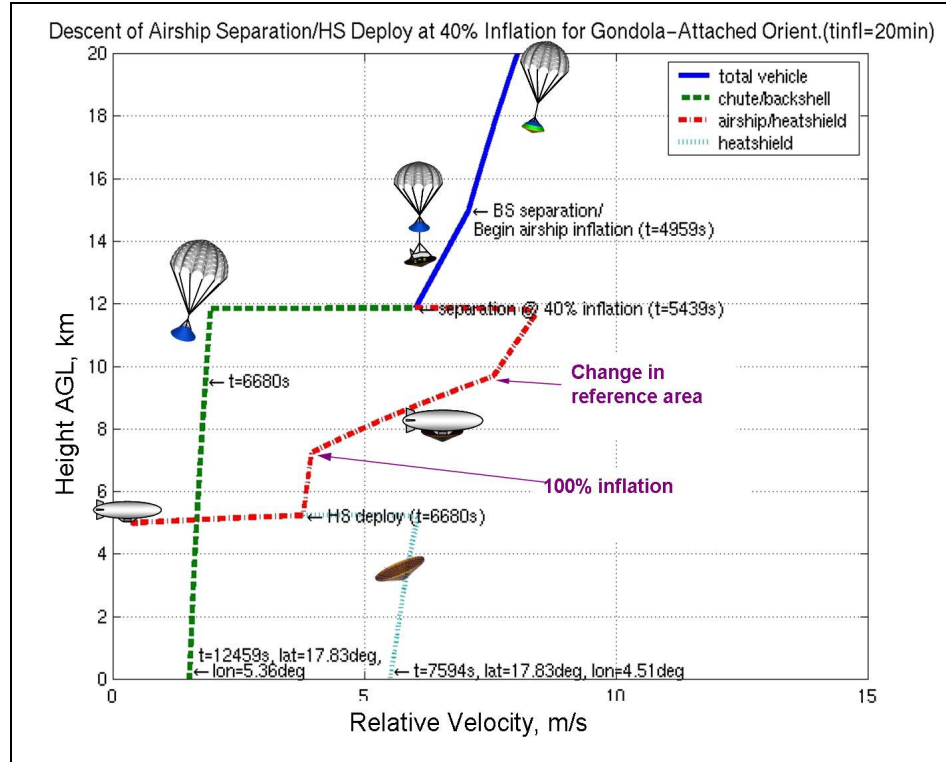

Figure 11. Case 3 3DOF POST2 Descent Trajectory

Figure 12 is the altitude profile for Case 3. The curve of the airship-heatshield changes slope which corresponds to the growth of effective area and full airship inflation. This case yields a greater separation in altitude of 4.25 km with time between heatshield deployment and airship-parachute common altitude of 42 minutes.
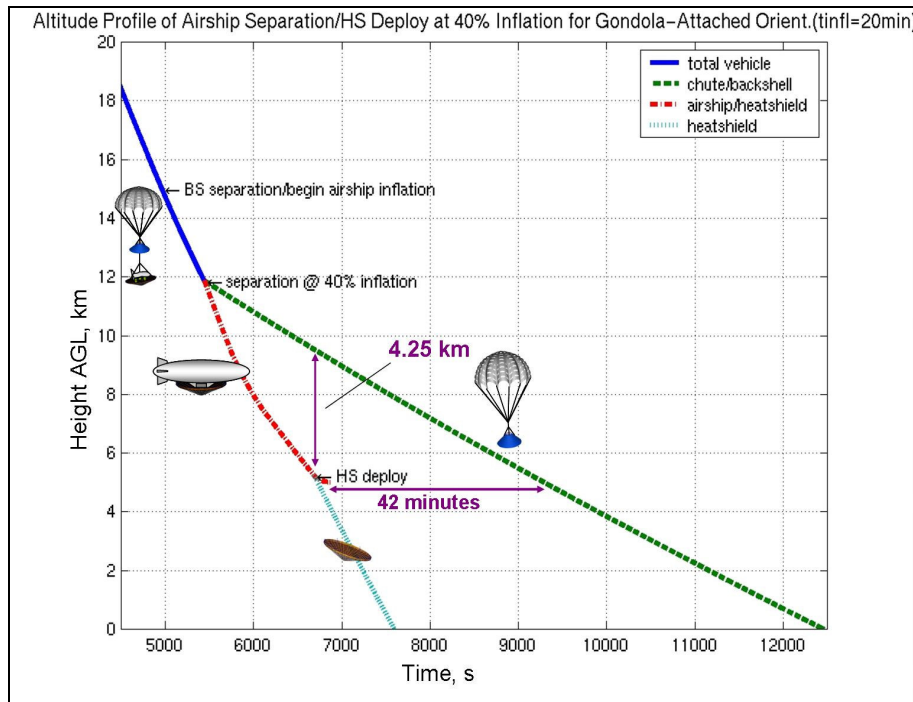
Figure 12. Case 3 3DOF POST2 Altitude Profile

Case 3 was the most desirable scenario out of all six cases because it has the largest separation in altitude between the two systems at heatshield deployment, yielding the largest margin. Also, from a collision avoidance standpoint, future designers may choose the Case 3 scenario to maximize the time (approximately 42 minutes) for the airship to maneuver to avoid potential recontact between the airship and parachute after heatshield deployment. The Case 2 scenario gives the least amount of time (approximately 19 minutes) for such maneuvers. Significant additional margin and a larger distance of separation at heatshield deployment are also possible for a nose-attached airship orientation by separating the airship prior to full inflation.

CONCLUSIONS

An airship buoyancy and inflation model has been developed to accurately integrate airship buoyancy and gasbag growth with the equations of motion of the nominal 3DOF EDL trajectory at Titan in POST2. The parachute remains active during inflation of the airship and separation. The airship inflation and buoyancy force implementation has been validated in the POST2 simulation in order to account for airship gasbag growth and initial level-flight effects on the trajectory. After tracking the parachute-backshell system and airship-heatshield system, for each of the six cases generated in POST2, both systems separate with a sufficient velocity change as to alter their paths to avoid collision throughout their nominal descent. The airship and heatshield also separate acceptably with an adequate distance of separation from the parachute-backshell system. This analysis demonstrates the feasibility of inflation of an airship on a parachute, for two different orientations, airship separation at various inflation times, and preparation for level-flight at Titan.

ACKNOWLEDGEMENTS

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