GNC 2008
7th International ESA Conference on Guidance, Navigation & Control Systems
2-5 June 2008, Tralee, County Kerry, Ireland

TITAN FLAGSHIP MISSION 3-DEGREE-OF-FREEDOM SIMULATION ANALYSIS

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INTRODUCTION

A NASA flagship mission to Titan, the largest moon of Saturn and the only moon in the solar system with a significant atmosphere, has been designed that uses three separate spacecraft, each requiring significant interaction with the atmosphere. The first vehicle is a Titan lander for lower-atmosphere and surface science. The second is an aerial vehicle for aerial science at approximately10 km altitude with an expected lifetime of one year. This spacecraft will use the natural winds of Titan to cover a large area over its lifetime. The third vehicle is a Titan orbiter that will interact with the atmosphere in two respects. The first atmospheric interaction is the orbital insertion maneuver that will be accomplished using aerocapture, during which time the hyperbolic approach of 6.5 km/s will be reduced to 1.6 km/s over 41 minutes with an exit periapsis altitude of 130 km. The second atmospheric interaction occurs after a propulsive maneuver has raised the periapsis after aerocapture to 1170 km, where the atmosphere will be sampled over several months. This is the first phase of aerosampling that covers southern latitudes. After a 3.3-year circular science phase at an altitude of 1700 km, a second phase of additional aerosampling is performed sampling northern latitudes. The atmospheric trajectory analysis for these three spacecraft will be discussed throughout this paper.

MISSION OVERVIEW

The flagship mission described in this paper is part of the analysis performed for the Titan Explorer mission [1]. The flagship Titan mission is designed to launch between 2015 and 2022 during one of multiple launch opportunities. For the mission described in this paper, arrival at Titan is assumed to be January 2, 2028. The lander and aerial vehicles enter 5 hours and 4 hours, respectively, prior to the beginning of the orbiter's aerocapture maneuver. The lander and aerial vehicle complete entry, descent and landing (EDL) and entry, descent, and deploy (EDD) while the orbiter/cruise stage provides communications coverage of these events. The orbiter then separates from the cruise stage 10 min prior to entry and uses aerocapture to establish the initial orbit about Titan.

The Titan lander enters the Titan atmosphere as a spin-stabilized ballistic entry vehicle, similar to the Huygens probe. It deploys a 3.65m diameter pilot parachute at Mach 1.3. A set time later, the backshell and pilot parachute are jettisoned and a main 12.1m subsonic parachute is deployed. After the heatshield is jettisoned a third landing 5.5m parachute is deployed. During terminal descent, bridles are lowered and airbags are inflated. Bridles are cut and the lander bounces to a halt on the Titan surface. Monte Carlo analysis of the EDL sequence shows a landing footprint of 720 x 220 km, well within the target terrain at the Belet dune region which is centered at approximately 10° S latitude and 110° E longitude and extends for at least 1800 x 900 km.

An aerial vehicle reaches atmospheric interface one hour after the lander atmospheric entry. The aerial vehicle is designed such that a Huygens entry and descent system is fitted with a balloon that inflates with entrained air and achieves buoyancy through MMRTG heating of the entrained air over a one-year in situ science phase. Like the lander system, it employs a 2.65-meter diameter aeroshell with a spin stabilized ballistic entry and later deploys a supersonic parachute (in this case 3.3-meter) and a subsonic chute (10.7-meter) before achieving balloon inflation.

The aerocapture phase of the orbiter mission is largely based on results from a peer reviewed 2003 NASA Titan Aerocapture Systems Study [2]. These results, as in the more recent trajectory assessment, use a high-fidelity simulation and show that 100% of the Monte Carlo cases successfully capture into Titan orbit. The final capture orbit targets a 1650km apoapsis altitude and uses 118m/s (3-sigma) ΔV to raise periapsis to the desired aerosampling orbit. The use of aerocapture provides a 54% reduction [3] in the required spacecraft mass to be delivered to Titan. Thus the additional mass required by the heatshield is more than offset by the fuel that would be required for propulsive capture.

The aerosampling phase of the Titan mission is separated into two phases. After the aerocapture to a 1630 km apoapsis altitude orbit, a periapsis raise maneuver is performed to increase periapsis altitude to 1120km. At this periapsis altitude, the first of two aerosampling phases begins. After 50-70 days, primarily because of the effect of the gravity of Saturn, the periapsis altitude decreases after which a periapsis raise maneuver of 46 m/s is performed to circularize to 1700km. The circular orbit is maintained for 3.3 years, after which the periapsis altitude is reduced to 900 km and the second phase of aerosampling begins. The duration of this phase is approximately 180 days. Two periapsis raise maneuvers are required during the second aerobraking phase to increase the periapsis altitude that decreases naturally due to Saturn's gravitational perturbations on the spacecraft.

SIMULATION TOOL

The simulation used for flight dynamics analysis of the Titan aeroassist is the Program to Optimize Simulated Trajectories II (POST2) [4]. This tool has vast heritage for mission analysis and flight operations. Some of this heritage extends to Mars missions such as Pathfinder, Mars Global Surveyor, Mars Odyssey, Mars Exploration Rovers, Mars Reconnaissance Orbiter, and Mars Phoenix. Other planetary missions include Genesis, Stardust, and Huygens, as well as various Earth flight vehicle applications. Capabilities of POST2 include launch, entry, horizontal and vertical flight, and it accommodates multiple gravity fields, external forces, and all phases of aeroassist. For the application described in this paper, additional models were required to represent aeroassist of a spacecraft to Titan. Applied models include a third body gravity perturbation of Saturn and a Titan atmosphere model, TitanGRAM. Further detail of the simulation models is provided in each aeroassist phase section.

TitanGRAM is an engineering model of the Titan atmosphere, also used for the Huygens entry probe assessment. It is based on data from Voyager fly-by, stellar occultation, and microwave and Hubble telescope data as well as updates from Huygens and Cassini. TitanGRAM allows for seasonal and latitudinal variations, measurement uncertainties and atmospheric perturbation statistical models. The TitanGRAM model provides an engineering estimate of the Titan atmosphere that is capable of Monte Carlo analysis and suitable for trajectory design. Reconstruction of the Huygens observed density profile showed good agreement with TitanGRAM. Variations of this model (e.g.MarsGRAM) have been used for several flight projects for many years. [5]

LANDER: ENTRY, DESCENT, AND LANDING

Upon arrival to Titan, the lander is the first vehicle to separate first from the cruise stage. The lander enters the Titan atmosphere at 6.48 km/s at 1000 km atmospheric interface with an entry mass of approximately 855 kg, (for comparison Huygens entry mass was 318 kg [6]) and then continues as a spin-stabilized ballistic entry vehicle, similar to the Huygens probe. The lander's entry flight path angle at atmospheric interface is -60.2°. The EDL sequence of events is based on previous missions' heritage: Huygens, Viking, Mars Pathfinder, and Mars Exploration Rovers. An illustration of the EDL phase is shown in Fig. 1.

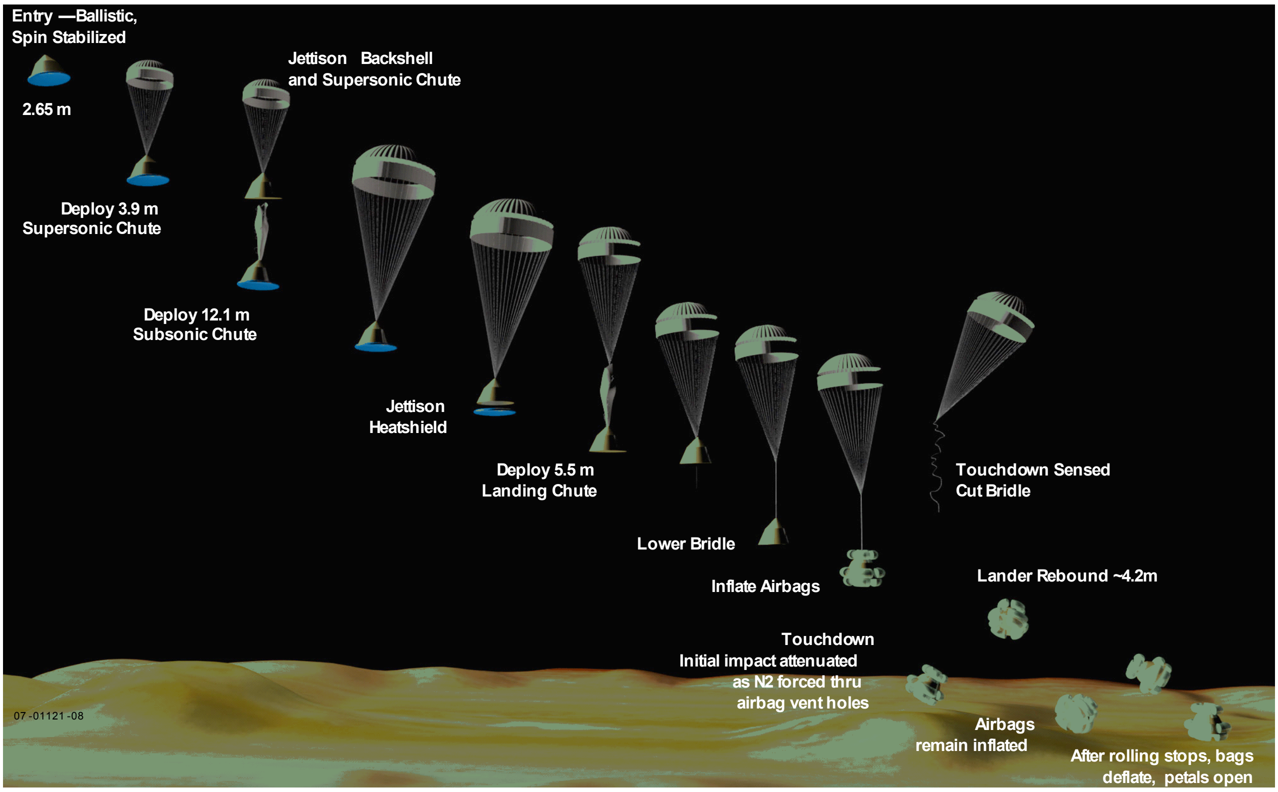

Fig. 1. Illustration of lander EDL sequence.

During the spin-stabilized hypersonic phase, the lander's nominal trajectory achieves a maximum stagnation point convective heat rate of 83 W/cm2 and a total heat load of 4300 J/cm2. This convective heating is determined by using the Sutton Graves relationship described in [7]. Its maximum deceleration reaches 14.4 g's in the four minutes within the atmosphere before the first parachute is deployed.

There are a total of three separate disk-gap-band parachutes on the EDL system. At approximately a 120 km altitude and Mach 1.3, a 3.9-meter diameter pilot parachute is mortar-deployed. At Mach 0.8, the backshell and pilot parachute are jettisoned and a main 12.1-meter diameter subsonic parachute is deployed at approximately 118 km above the areoid. The nominal dynamic pressure at the main parachute deploy is 285 N/m^2. After the heatshield is jettisoned a third landing 5.5-meter parachute is deployed at approximately 115 km above the surface. This final parachute diameter was chosen such that the landing velocity requirement of 4 m/s at touchdown was met. During terminal descent, bridles are lowered and airbags are inflated. Bridles are cut at a few meters above the surface and the lander bounces to a halt on the Titan surface. Landing occurs nominally at -8.5° latitude and 118°E longitude. Total descent time from atmospheric entry to landing is 2.9 hours.

EDL Monte Carlo Performance

A Monte Carlo trajectory analysis simulating 2000 trajectories has been performed for the Titan landing vehicle. The lander design is based on the Apollo/CEV capsule configuration [8]. The aerodynamic database of the lander is based on CEV simulations and included dispersions as defined by that project [8]. The uncertainties in the Monte Carlo include dispersions on entry flight path angle of +/- 2.5º 3-sigma (all uncertainties hereafter are defined as 3-sigma values). These values were estimated by the Jet Propulsion Laboratory (JPL) by performing a detailed mission design from launch to entry interface. Atmospheric uncertainties, based on the Huygens entry, were applied as well as a Flasar mean wind profile [9] with dispersions upon wind azimuth and magnitude. Uncertainties were also applied to the drag coefficients of the three lander parachutes based on parachute drag coefficient analysis for the Mars Phoenix lander.

Performance indicators show the lander system remains within all design requirements [1]. Thermal parameters during the lander entry indicate that the aeroheating is also within system requirements. The maximum convective heat rates during the hypersonic phase as shown in Fig. 2-a) are 84 +/- 5 W/cm^2, while the heat load throughout the hypersonic phase as shown in Fig. 2-b) is 4300 +/- 250 J/cm^2. The heat rates were estimated using a Sutton Graves relationship that was tuned for the Titan's atmospheric constituents [10]. The maximum dynamic pressure the vehicle obtains during entry in Fig. 2-c) is 13200 +/- 2000 N/m^2. Fig. 2-d) shows the entry deceleration is 14 +/- 2 g's).

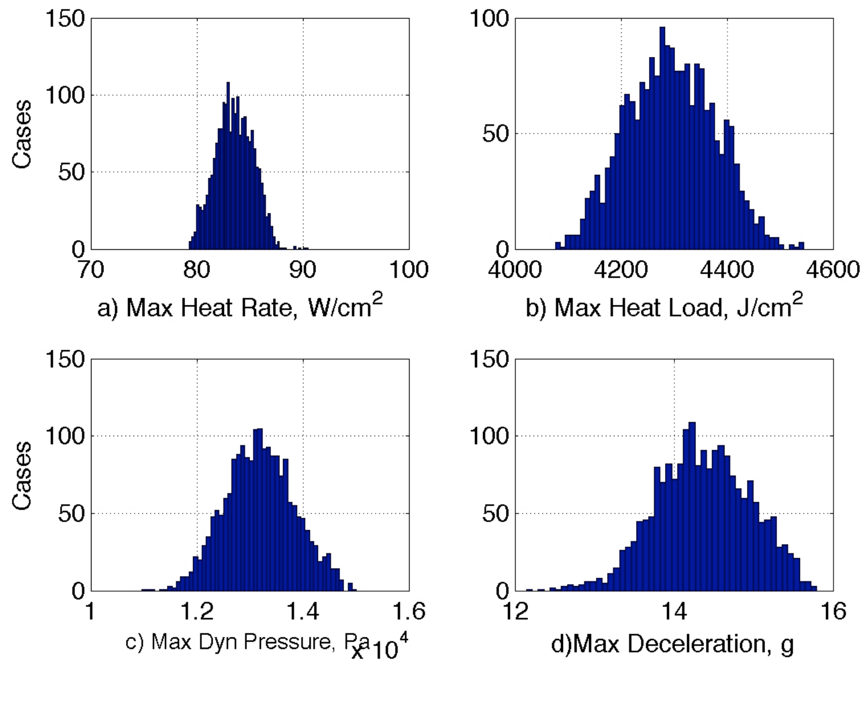

Fig. 2 Hypersonic heating results of lander EDL

A key parameter of interest in previous entry, descent, and landing (EDL) missions has been the opening loads of the parachutes within the atmosphere. This parameter is directly related to the dynamic pressure at which the parachute inflates. A simple algorithm was used to estimate the opening loads of the parachutes based on Viking, Mars Pathfinder, Mars Exploration Rovers wind tunnel and flight data. The equation for the opening loads force of each parachute's inflation is shown in equation 1 [11].

$$F_P = qC_{D0}S_0C_x\left(\frac{t - t_{LS}}{t_{FI} - t_{LS}}\right)^n \tag{1}$$

where q is the dynamic pressure, C_{D0} is the parachute drag coefficient. In this simulation, the parachute drag coefficient a linearly interpolated table of drag coefficient versus Mach number, the same table that was used in Mars Phoenix simulation. Also in equation 1, S_0 is the parachute area, C_x is the opening load factor, here equal to 1.344, t indicates the current time or time of either line stretch (t_{LS}) or full inflation (t_{FI}). The parameter n is the exponent in the inflation model, here 4 is used. More details of the parachute inflation models can be found in [11]. The dynamic pressures at the three parachute deploy points are less than 760N/m^2, 330N/m^2, and 15N/m^2 respectively, as shown in Fig. 3. In this figure, the two plots on the left are for the drogue parachute, the middle plots indicate the data for the main parachute, and the right-hand plots are for the landing (terminal) parachute.

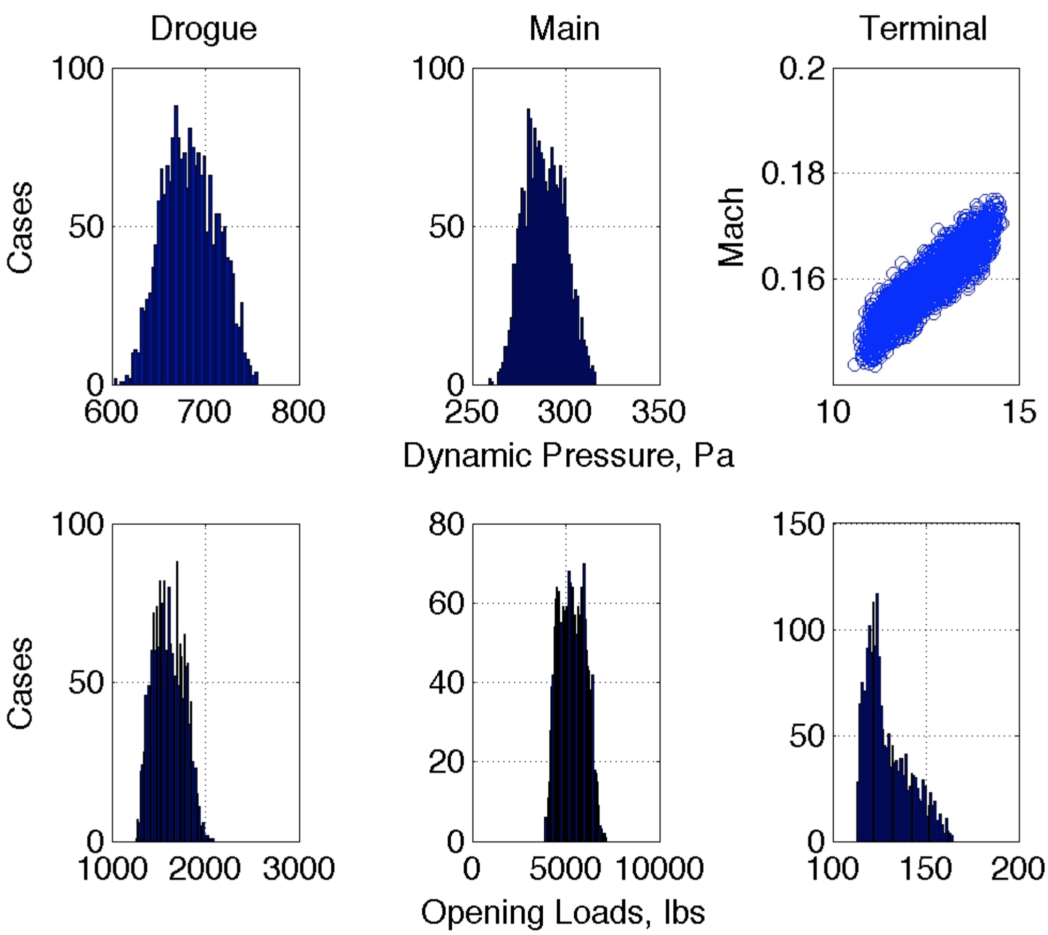

Fig. 3. Dynamic pressures and opening loads of three EDL parachutes

Monte Carlo results also show that the velocities at touchdown are less than 4 m/s in the vertical direction and less than 2 m/s in the horizontal direction, as shown in Fig. 4. The horizontal velocities at touchdown are primarily due to the Flasar wind model used and the uncertainties of this wind model. Additional results of this Monte Carlo analysis show a landing footprint of 720 km x 220 km within the Belet region as shown in Fig. 5.

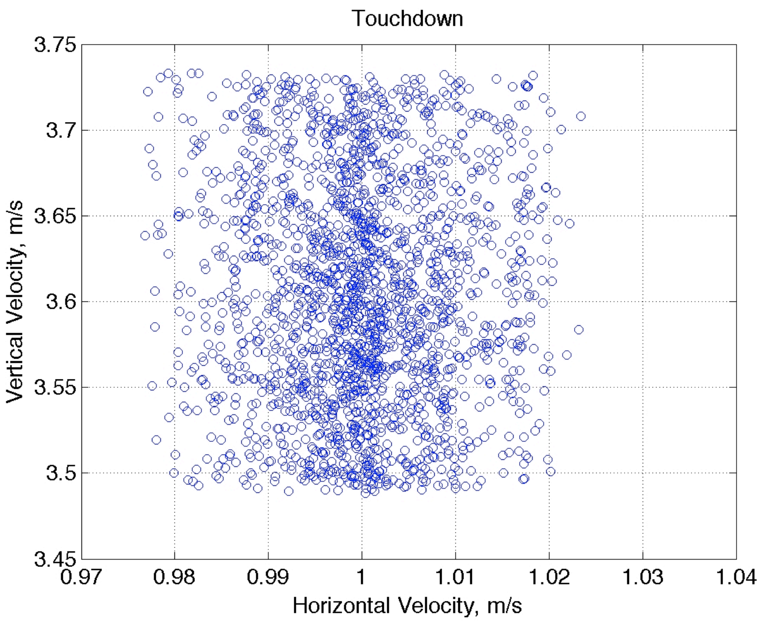

Fig. 4. Landing velocities of Titan lander.

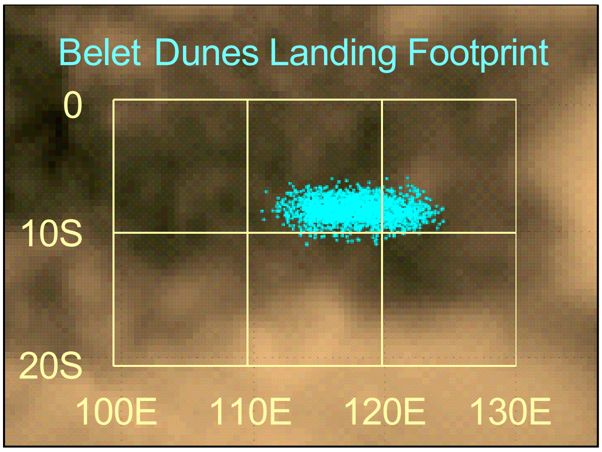

Fig. 5. Landing footprint in Belet dune region

AERIAL VEHICLE: ENTRY, DESCENT, AND DEPLOYMENT

The entry and descent phases for the aerial vehicle are similar to the lander's entry and descent with a 2.65-meter diameter aeroshell spinning in a ballistic entry throughout its hypersonic phase. There are two disk-gap-band parachutes: the 3.3-meter diameter drogue parachute deploys a set time before a 10.7-meter diameter main parachute is deployed, decreasing the spacecraft velocity to 13 m/s at 5-10 km altitude above the areoid before initiating the balloon inflation. The entry, descent and deployment (EDD) sequence of events is shown in Fig. 6.

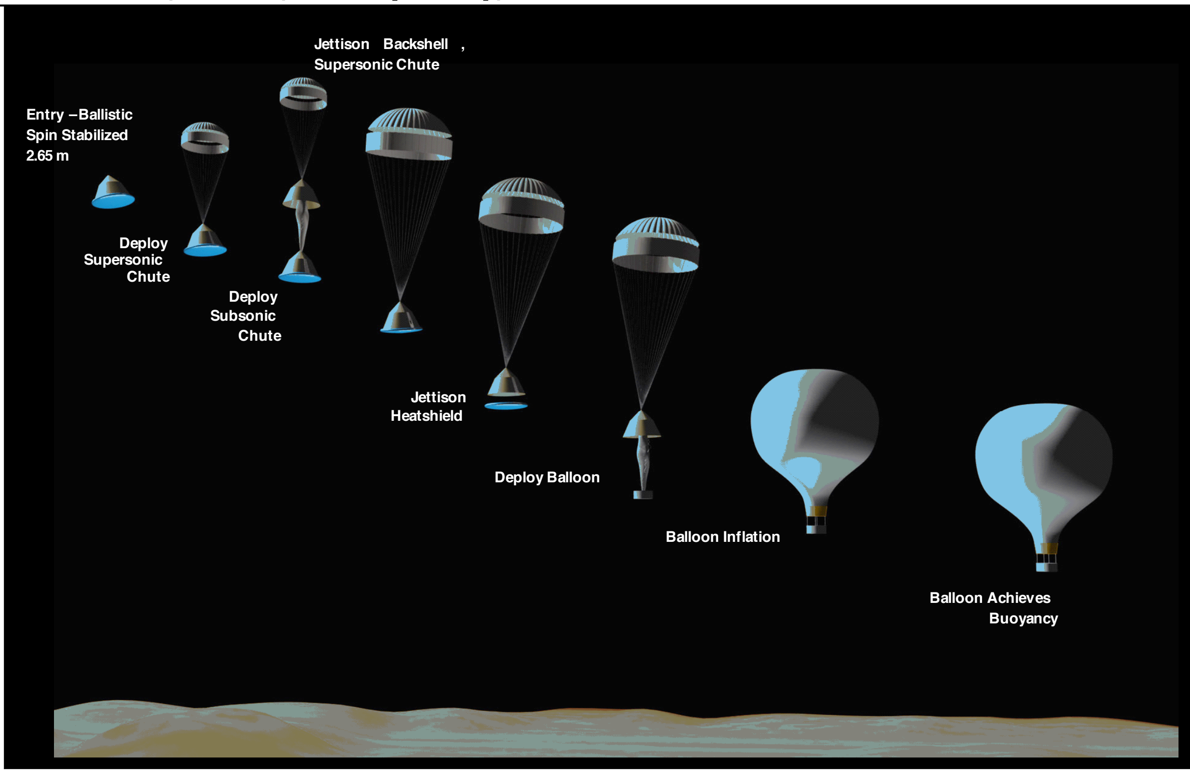

Fig. 6. Illustration of EDD sequence of events.

The balloon was modeled as a six-meter radius sphere, with the internal gas heated by the onboard nuclear power source. For this analysis, the temperature of the gas within the balloon was assumed to be heated to a temperature 9 deg K higher than ambient. This temperature increase is required to maintain a minimum altitude of 5 km for the one year of operations.

Monte Carlo statistics of the entry and descent portion of the aerial vehicle show hypersonic aerothermal parameters similar to that of the lander: maximum heat rates during the hypersonic phase of 99 +/- 8 W/cm^2, heat loads of 4600 +/- 260 J/cm^2, and decelerations of 14 +/- 2 g's. Drogue parachute opening loads are 3020 +/- 900 lbs at 1050 +/- 120 N/m^2 in dynamic pressures at 111 km. Main parachute opening loads are 1300 +/- 700 lbs at 60 +/- 30 N/m^2 dynamic pressures at 98 km.

The EDD of the aerial vehicle is modeled for one year of operations and simulated through Monte Carlo analysis for seven days to generate near-term risk assessment. The one-year trajectory (Fig. 7) shows the nominal variation of the balloon with altitude with season and local time over the duration of the operations phase. The Monte Carlo shows the variability in the balloon altitude at deployment and the variability of the entry vehicle during entry and decent. Monte Carlo results indicate that the balloon-deploy altitude ranges from 5 km to 10 km and the balloon short-term operational altitudes range from 4 to 11 km. Over the one-year operational phase the nominal variation in altitude is 5 to 13 km as shown in Fig. 7. Atmospheric temperatures in this one-year operations phase range from 80 K to 88 K as altitudes and latitudes vary.

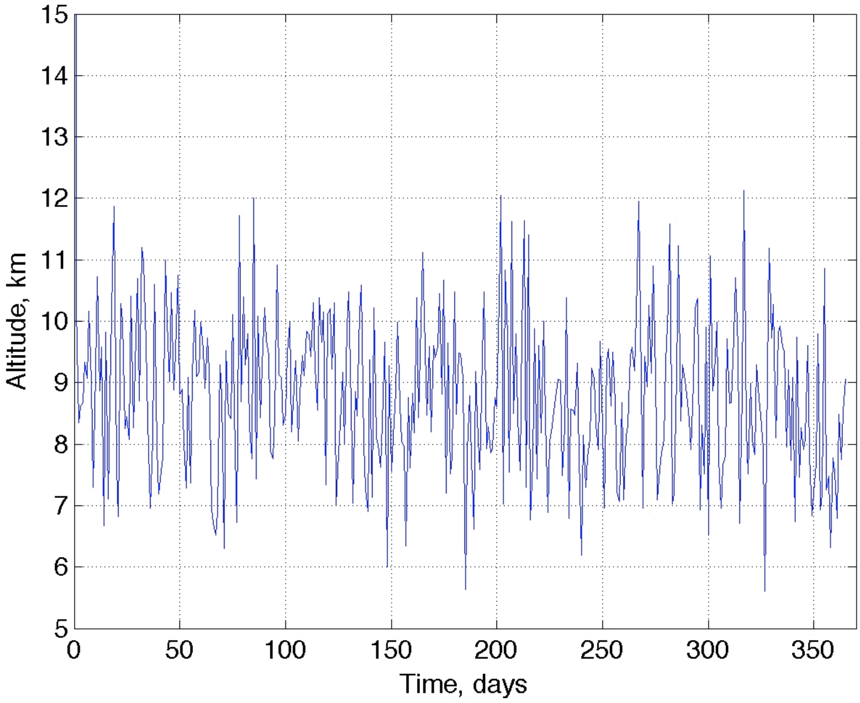

Fig. 7 Altitude profile of year-long balloon operations

ORBITER: AEROCAPTURE

The last vehicle to enter the Titan atmosphere is the orbiter. The orbiter first utilizes the Titan atmosphere to obtain orbit insertion via aerocapture. Aerocapture is used to change the incoming hyperbolic orbit to an elliptical orbit, using atmospheric drag to reduce the velocity from 6.5 km/s to 1.6 km/s at the end of the aerocapture phase. This simulation modeled a candidate guidance algorithm and a pseudo controller to control the atmospheric exit conditions to minimize the required ΔV to initiate the first aerosampling phase. An illustration of aerocapture is shown in Fig. 8.

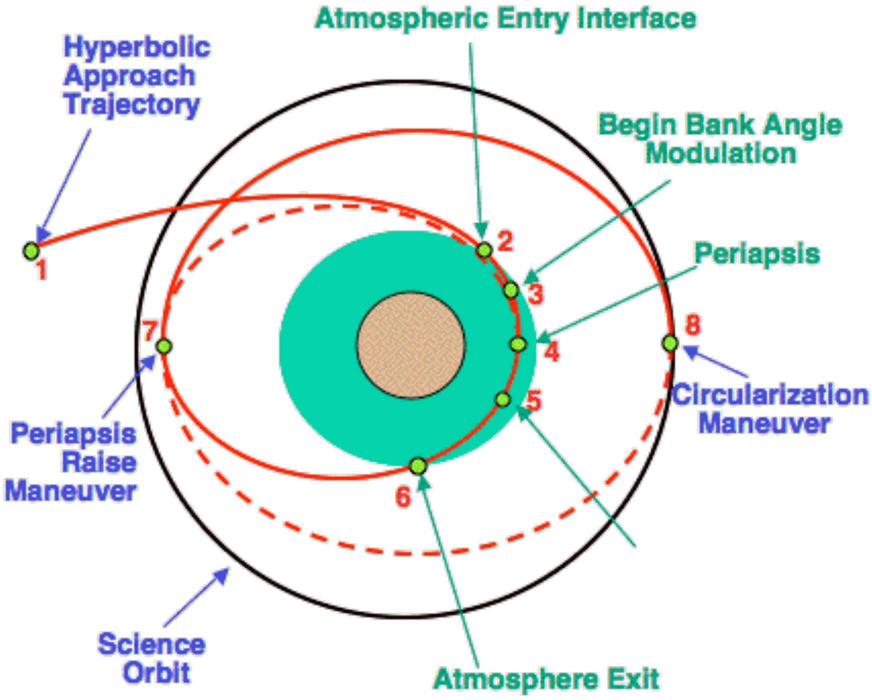

Fig. 8. Illustration of aerocapture sequence of events.

The orbiter approaches the aerocapture phase at the desired flight path angle. An autonomous guidance algorithm modulates the aerodynamics of the orbiter to alleviate the effects of the variable atmosphere. A Terminal Point Controller (TPC) guidance algorithm was used in the Monte Carlo assessment of the Aerocapture phase. The TPC uses bank control to guide a lifting vehicle to a desired apoapsis and inclination. TPC is a feedback guidance that uses sensitivities of the exit condition to changes in the state and control to determine the control at any point along the trajectory. The sensitivities are generated from a reference trajectory that is determined off-line prior to flight. TPC has an in-plane component that targets the velocity increment required to achieve a desired orbit after the atmospheric pass is complete (ΔV) and an out-pf-plane component that targets inclination. This algorithm is a derivative of the algorithm used in the Apollo program and the MSL entry guidance. TPC has been studied extensively for several proposed Aerocapture missions [12].

A Monte Carlo trajectory analysis of 2000 simulated trajectories was performed on the orbiter aerocapture system. The orbiter enters the Titan atmosphere at 1000km above the areoid at a -35° flight path angle with an inertial velocity of 6.5km/s. Dispersions were modeled in entry state, aerodynamics, and atmosphere similar to the previous 2003 Titan Systems Analysis study [2]. Flight path angle dispersions for this study were held to -35 +/- 0.37° (3-sigma). These values were estimated similarly to the lander entry statistics: JPL performed a detailed mission design from launch to orbiter entry interface. The TitanGRAM dispersed atmosphere model parameters also reflect knowledge gained from the Huygens entry.

Statistics on the Aerocapture phase shown in Fig. 9 indicate maximum convective heating rates of 35 +/- 1 W/cm^2 (Fig. 9-a), show heating loads of 6760 +/- 136 J/cm^2 (Fig. 9-b), maximum dynamic pressures of 2020 +/- 95 Pa (Fig. 9-c), and decelerations of 2.5 +/- 0.1 g's (Fig. 9-d). The duration of the aerocapture phase from atmospheric entry to exit is 41 +/- 28 minutes.

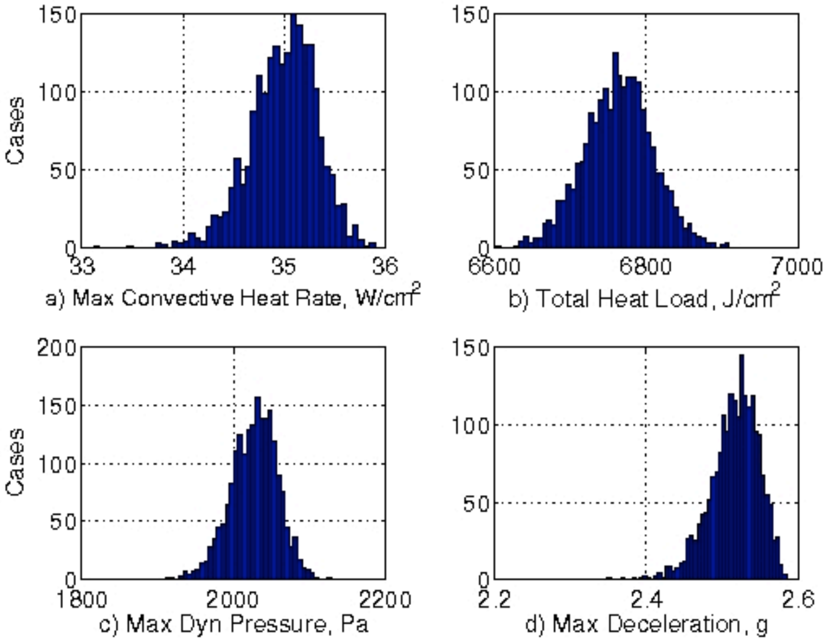

Fig. 9. Aerocapture heating statistics

Two maneuvers are planned after aerocapture to modify the orbit from a nominal post-aerocapture state of 1675 km apoapsis, 130km periapsis to a 1630km apoapsis 1160km periapsis in preparation for the first phase of aerosampling, discussed in the section below. These two maneuvers nominally require 128 m/s total (8 m/s for the apoapsis change, 120 m/s for the periapsis raise) with a 3-sigma high value less than 135 m/s. The histograms of each maneuver are shown in Fig. 10 c) and d).

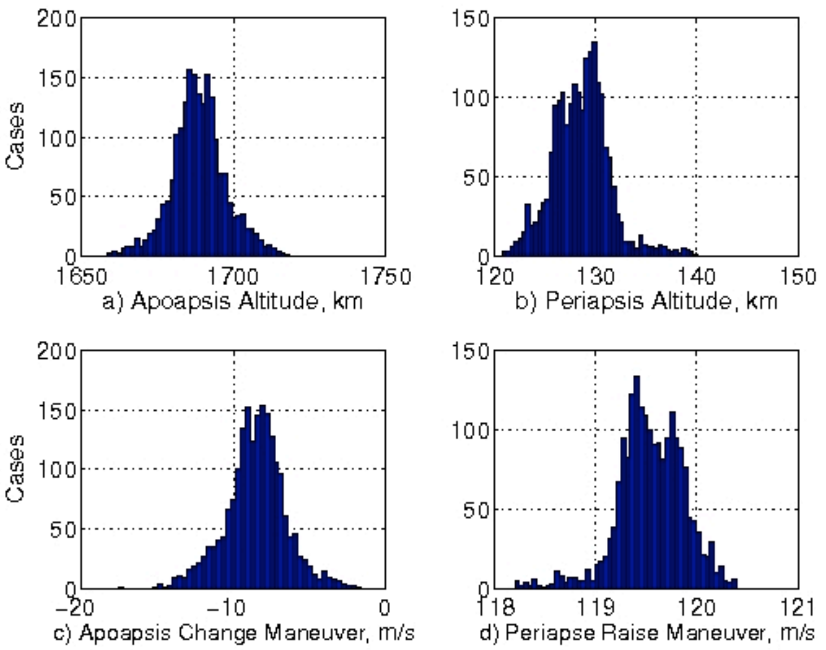

Fig. 10. Aerocapture atmospheric exit conditions

ORBITER: AEROSAMPLING

The Titan aerosampling design is composed of two phases with the one-year circular orbit design separating the phases. Aerosampling phase 1 begins immediately following the orbiter aerocapture and propulsive clean-up into a 1630km x 1170km elliptical orbit. The orbiter's periapsis precesses from lower southern latitudes towards equatorial regions with 20 deg latitudinal ground coverage achieving periapsis densities within 0.2 and 0.8 kg/km^3, as shown in Fig. 11. Periapsis altitudes of 1000 km to 1200 km are sampled within Phase 1 allowing for a broad spectrum of scientific analysis of these atmospheric levels. This phase is designed to begin aerosampling at 1650 km in apoapsis altitude since the orbiters orientation with Saturn results in a naturally increasing apoapsis altitude and no propulsive maneuver is necessary to alter the apoapsis altitude for the circular orbit phase. In 60 days, when the apoapsis altitude has reached 1700km, a 63 m/s propulsive maneuver is made at apoapsis to raise periapsis and circularize the orbit.

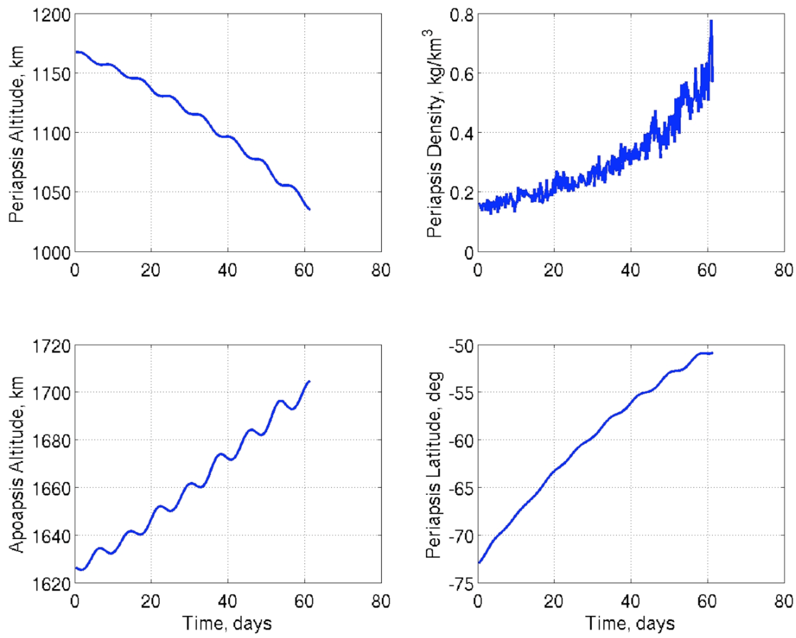

Fig. 11. Aerosampling Phase 1 orbital parameters

After the circular orbit phase, a second aerosampling phase begins, sampling northern latitudes that were not studied during phase 1. Phase 2 is longer in duration and requires two periapsis raise propulsive maneuvers during the aerosampling phase with a total of 45 m/s to extend the latitude coverage. In 177 days 40 degrees of northern latitudes are sampled within a 0-5 kg/km^3 density range, as shown in Fig. 12. This density range provides less than 1.5e-3 W/cm^2 in aeroheating on the spacecraft, 2-3 orders of magnitude decrease in heating from the Mars Odyssey or Mars Reconnaissance Orbiter aerobraking missions [13,14]. Following the second phase of aerosampling, 88 m/s is required to circularize the orbit to the 1700 km science orbit for 3.3 years.

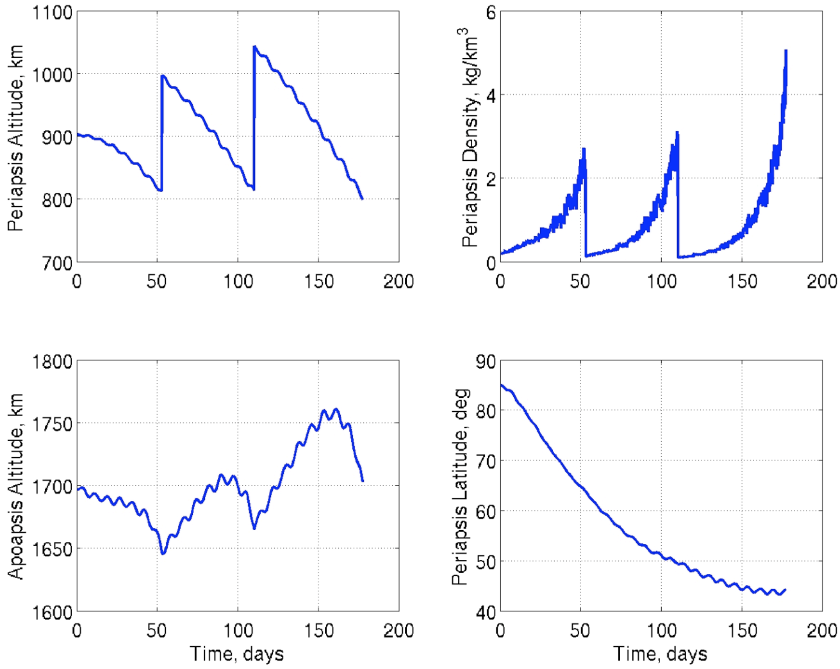

Fig. 12. Aerosampling Phase 2 orbital parameters

SUMMARY/CONCLUSIONS

This Titan Explorer mission is designed to utilize the Titan atmosphere to safely arrive at Titan for scientific data collection. The first vehicle, a lander, with heritage design from Huygens and successful Mars lander missions, bounces to the ground with airbags after EDL. The second vehicle, a balloon, achieves entry, descent, and deployment as it inflates for a one-year mission sampling the lower atmosphere of Titan. The third vehicle, an orbiter, uses both aerocapture to achieve an initial elliptic orbit; and then the orbiter spends months sampling the upper atmosphere of Titan before and after a 3.3-year circular science phase.

Each adaptation of Titan aeroassist safely meets all performance and science requirements defined by the Titan Explorer Mission.

ACKNOWLEDGEMENTS

The authors would like to thank the Titan Explorer Team led by the Johns Hopkins University Applied Physics Lab for the design of this mission concept and for the opportunity to participate in this Titan Explorer Study Team.

NOMENCLATURE

F_P	parachute opening load force
q	dynamic pressure, N/m2
C_{D0}	parachute drag coefficient
S_0	parachute area, m2
C_x	parachute opening load factor
t	time, sec
t_{LS}	time of line stretch, sec
t_{FI}	time of full inflation, sec
n	parachute opening load force model exponent

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