

# Comparison of Transition to Flight Methods for a Titan Helicopter



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

Author  
Ravi Prakash

Advisor  
Dr. Robert D. Braun  
Space Systems Design Lab (SSDL)

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# Comparison of Transition to Flight Methods for a Titan Helicopter

Ravi Prakash<sup>\*</sup>

*Georgia Institute of Technology, Atlanta, GA, 30332*

**T**wo methods of transition to flight for a Titan helicopter were compared: a lander option and a mid-atmospheric deployment. The methods were compared based on the ability of each to allow the helicopter to successfully commence flight as well as satisfy the mass and volume constraints of the aeroshell. Landing the helicopter before its initial flight proved too massive for the baseline mission, but an acceptable solution was found with a smaller helicopter that could achieve a heavily compromised mission. A mid-atmospheric deployment satisfied all the criteria while allowing enough mass for the helicopter to achieve its baseline mission. Although it was the higher risk option, the ability of the mid-atmospheric deployment to achieve the baseline mission was the defining factor in its choice as the transition to flight method for the Titan helicopter.

## I. Introduction

“I was on the point of cutting the cord that suspended me between heaven and earth . . . and measured with my eye the vast space that separated me from the rest of the human race . . . I felt myself precipitated with a velocity that was checked by the sudden unfolding of my parachute.”

— André-Jacques Garnerin, world's first parachutist, 22 October 1797.

CURIOSITY of the unknown is what drives humans to explore. The Titan Explorer project will continue the exploration of the unknown by exploring Titan’s atmosphere, clouds, haze, surface, and any possible oceans, including the chemical and pre-biological chemistry of each.<sup>1</sup> To do this, the mission requires an aerial vehicle capable of covering a range of over 50 km with a duration of 1 – 4 months. Two options are being considered for the aerial vehicle by a NASA Vision Mission Study: an airship and a helicopter.<sup>1</sup> The Space Systems Design Laboratory at the Georgia Institute of Technology has been tasked with designing the helicopter platform for this mission.

The purpose of this 8900 project was to determine the most favorable method of transition to flight for a Titan helicopter. Titan’s dense atmosphere (roughly four times that of Earth) coupled with its low gravity (roughly one-seventh of the Earth’s gravity) allows an array of entry, descent, and transition (EDT) options to be considered. Two methods were explored for this study. The first method that was considered was landing on the surface of Titan before commencing flight. The second method that was considered was a mid-atmospheric deployment of the helicopter from the aeroshell. Both of these approaches have advantages and disadvantages. To determine which should be selected for the Vertical Takeoff and Landing

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<sup>\*</sup> Graduate Research Assistant, Guggenheim School of Aerospace Engineering, Georgia Institute of Technology

(VTOL) option of the Titan Explorer project, a qualitative and quantitative comparison of two entry methods was performed.

This report will discuss the advantages and disadvantages of each system as well as review the analysis and results of the transition methods. This report will also discuss how the choice in transition to flight method affects both the vehicle and mission.

## II. Approach

### A. Assumptions

The design of the helicopter was limited by the mass allocation and volume of the aeroshell. The allocated mass inside the aeroshell was 400 kg. This amount includes the helicopter, attachments to the aeroshell, transition to flight system (lander or mid-atmospheric deployment system), and a 30% mass margin. Therefore, the maximum expected allocated mass cannot exceed 307.7 kg. An 11.4 kg parachute was provided by NASA LaRC and did not count against the mass allocation. A helicopter was designed to achieve the baseline mission of a 50 km range at a 10 km altitude ceiling with an endurance of 1 – 4 months, and had a maximum expected mass of 245.2 kg. The basic dimensions of this helicopter are given below in Table 1.

**Table 1 Baseline Helicopter Dimensions**

Dimension	Value (m)
Fuselage Length	2.6
Fuselage Width	1.0
Fuselage Height	1.0
Tail Length	0.75

By relaxing the requirements to achieve a minimum acceptable mission of 1 km range and 1 km ceiling, and reducing the payload from 36.0 kg to 15.0 kg, the helicopter had a maximum expected mass of 151.1 kg. The dimensions for this helicopter are given below in Table 2.

**Table 2 Reduced Mission Helicopter Dimensions**

Dimension	Value (m)
Fuselage Length	1.4
Fuselage Width	0.7
Fuselage Height	0.7
Tail Length	0.75

The mass breakdown inside the aeroshell for the baseline mission and minimum acceptable mission are shown in Table 3 and Table 4.

**Table 3 Mass Breakdown – Baseline Mission**

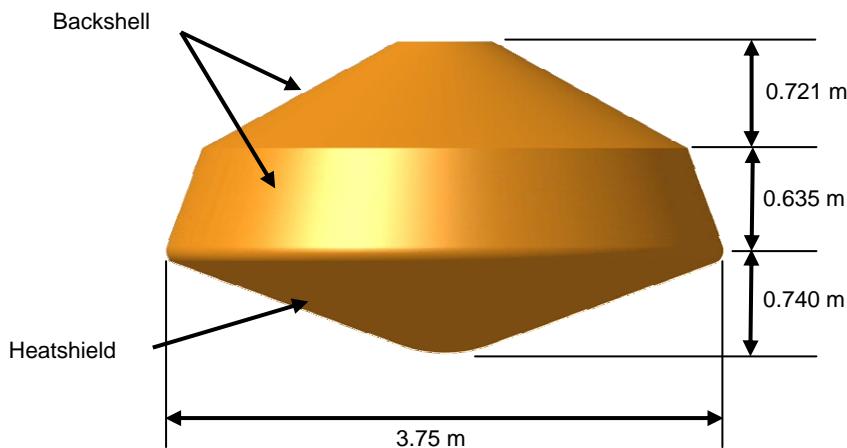
<b>Component</b>	<b>Maximum Expected Mass (kg)</b>
Helicopter	245.2
Aeroshell Connections	30.0
Available Mass for Transition to Flight System	32.5
<b>Total Aeroshell</b>	<b>307.7</b>

**Table 4 Mass Breakdown – Reduced Mission**

<b>Component</b>	<b>Maximum Expected Mass (kg)</b>
Helicopter	151.1
Aeroshell Connections	18.5
Available Mass for Transition to Flight System	138.1
<b>Total Aeroshell</b>	<b>307.7</b>

From Table 3 and Table 4, it is seen that the baseline mission does not leave much mass for a bulky transition to flight system. The reduced mission allows more mass for a heavier transition to flight system. This analysis will determine if a compromise will have to be made to the mission to accommodate either transition to flight option.

The helicopter and transition to flight system were required to fit inside a pre-specified aeroshell. The basic dimensions of this aeroshell are shown in Figure 1 below, with the aeroshell mass breakdown shown in Table 5. For completeness, the parachute mass is included separately in this table.

**Figure 1 Aeroshell Dimensions**

**Table 5 Aeroshell Mass Breakdown**

<b>Component</b>	<b>Maximum Expected Mass (kg)</b>
Heatshield	251.5
Backshell	98.3
Pallet Ring	57.7
Separation Ring	16.2
Separation Ring Attachments	9.7
Parachute	11.4
<b>Total Aeroshell</b>	<b>444.8</b>

A single supersonic parachute was provided on the aeroshell. The fully inflated parachute profile is semi-spherical with a surface area of  $25.95 \text{ m}^2$  ( $5.75 \text{ m}$  diameter) and  $C_{D0}$  of 0.525. The parachute material is a combination of Dacron and Kevlar with a total mass of 11.4 kg. In the mid-atmospheric deployment analysis, parachutes of various diameters will be analyzed to determine if the given parachute is optimal in terms of performance and mass for this mission.

The entry, descent, and transition (EDT) analysis began at the top of Titan's atmosphere, which was assumed to be 1000 km. An atmospheric model similar to the Yelle model, but updated using data from the recent Huygens mission, was used.<sup>2</sup> Additional Titan-specific data used were the moon's radius ( $R_T$ ), rotation rate ( $\Omega$ ), surface gravity ( $g_0$ ), and gravitational parameter ( $\mu$ ). These values are given below in Table 6.

**Table 6: Titan Data**

<b>Parameter</b>	<b>Units</b>	<b>Value</b>
$R_T$	km	2575.0
$\Omega$	rad/sec	$1.64 \times 10^{-4}$
$g_0$	$\text{m/s}^2$	1.35
$\mu$	$\text{m}^3/\text{s}^2$	$8.98 \times 10^{12}$

The aeroshell is assumed to perform a lifting entry into Titan. For this entry, certain vehicle-specific parameters were defined to specify the trajectory. These parameters are (at the atmospheric interface of 1000 km) the entry mass ( $m_0$ ), inertial flight path angle ( $\gamma_0$ ), inertial velocity ( $V_0$ ), azimuth (Az), geocentric latitude ( $\phi$ ), and planet-relative longitude ( $\theta$ ), as well as the aeroshell's  $C_L$ ,  $C_{D0}$ , and reference area ( $A$ ). The values of these parameters are given in Table 7.

**Table 7 Vehicle Parameter Values at Titan Entry**

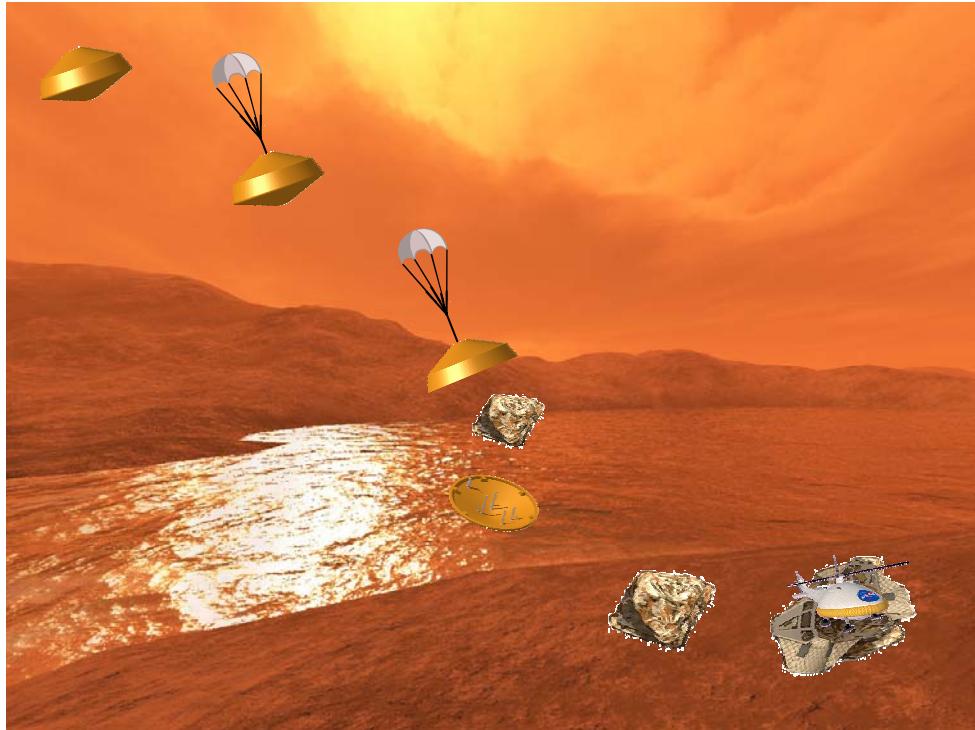
Parameter	Units	Value
$m_0$	kg	844.8
$\gamma_0$	deg	-50.0
$V_0$	m/s	6500
Az	deg	0.0
$\phi$	deg	0.0
$\theta$	deg	0.0
$C_L$	-	0.365
$C_{D0}$	-	1.460
A	$m^2$	11.045

For the trajectory analysis, it was assumed that the entire allocated mass inside the aeroshell was used. Therefore, the entry mass consisted of the aeroshell, parachute, and allocated mass, and amounted to 844.8 kg.

## B. Analysis

### 1. Option I: Landing

The first transition to flight alternative that was explored was the landing option. In this option, the helicopter is inside a lander, which is inside the aeroshell. The parachute will be released from the backshell at Mach 1.1 (approximately 149 km altitude). The lander will be released from the aeroshell at an altitude of 3 km. Because the density increases with decreasing altitude, the velocity of the aeroshell will be slower at lower altitudes. 3 km was chosen as lander release altitude because it is the lowest altitude that no terrain will be assumed. At this time, the helicopter is inside the lander and has no parachute. The lander will be made buoyant with an inflatable flotation device in case it lands in liquid methane. The flotation device will be an inflatable tube filled with helium, and will be inflated immediately after the lander has exited the aeroshell. Having the helicopter inside the lander will protect the helicopter in the event that the parachute does not deploy properly. Once the lander lands, it will orient the helicopter in an upright position so that it may takeoff properly. A schematic of this process is shown in Figure 2.



**Figure 2 EDT Schematic for Landing Option**

An obvious advantage of landing before flight is that the helicopter would have ample time to check all its subsystems once it landed. If a problem was found in any one of the subsystems, the ground control on Earth could determine the best strategy for fixing the problem. In this scenario, the amount of time to fix the problem is limited by the available power and telecom duration with the orbiter.

Another advantage of landing before the initial takeoff is in the area of parachute failure. The lander system is designed to withstand the impact loads at the surface of Titan if the parachute does not deploy properly. However, this advantage carries with it the possibility of additional structural mass to withstand the impact loads. The structural mass may not change if the loads during the surface impact are less than the loads encountered during launch or entry.

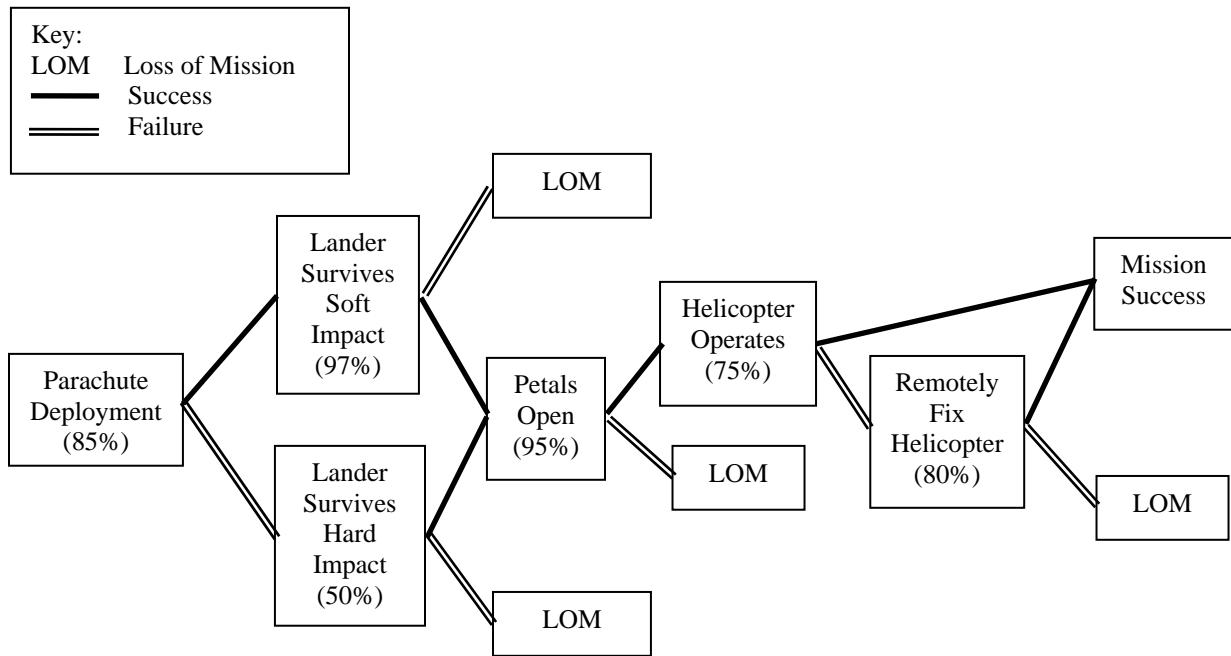
A major disadvantage of landing first is the complexity involved. The helicopter must be on a relatively flat surface in order to takeoff. The helicopter was designed to be able to produce enough vertical thrust to hover if it landed on an incline of no more than  $10^\circ$ . Therefore, an incline of greater than  $10^\circ$  could prevent the helicopter from taking off.

Additional complexities are involved when one considers the orientation of the helicopter upon landing. When the helicopter comes down inside the lander, it may not be upright when it comes to a stop on the surface. Many factors can influence this outcome, including the possibility of the vehicle initially impacting a mountain and then rolling down, or the aeroshell landing slanted on a level surface. In this case, a complicated and possibly massive system would have to be developed to ensure that the helicopter could make itself upright. Such a system was developed for the Mars Exploration Rovers, and the entire landing system (airbags, petals, etc) had a mass of about 348 kg, twice the mass of the Rover itself.<sup>3</sup> Although the gravity and atmospheric density on Titan lead to a much lower impact velocity than it would on Mars,

the bulk of the mass of the MER landing system came from the need to withstand the launch loads. Therefore, one might expect a similar mass fraction for the helicopter landing system.

Also, the lander and helicopter system has to be made buoyant in the event that it lands in liquid methane. This can be done by including an inflatable flotation device around the lander. The lander would also have to be weighted so that the helicopter would be upright inside the lander when it opened, allowing the helicopter to takeoff. These constraints add restrictions to the helicopter mass and volume. The numerous disadvantages of the landing option cause many design changes in the helicopter which limit its size to fit inside the aeroshell.

A diagram showing the possible failure modes for the landing option is shown in Figure 3 below. Probabilities of success for each failure mode were assigned by the author based on intuition, and should not be taken as absolute numbers.



**Figure 3 Fault Tree for Landing Option**

The fault tree shows that for the lander, there are contingencies that will allow for mission success for certain failures. There are four mission critical events that should they fail, will lead to a loss of mission. The probability for a loss of mission is about 18.8%.

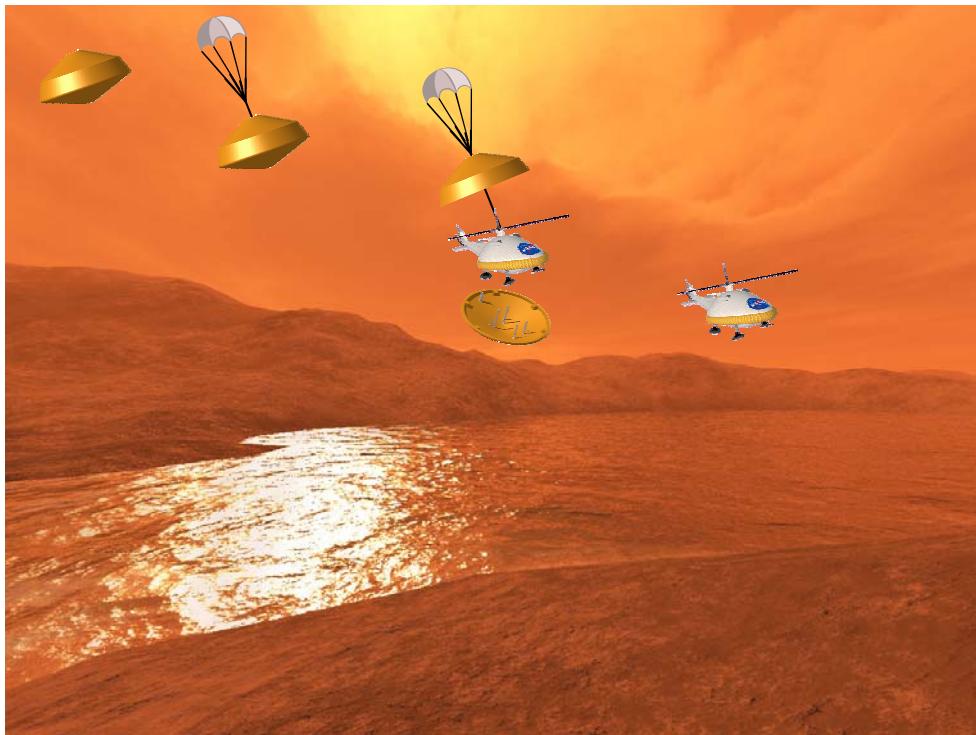
The quantitative analysis for the landing option consisted of inputting the Titan data and parameter values from Table 6 and Table 7 in a NASA developed code called Program to Optimize Simulated Trajectories (POST). The data were analyzed to determine the conditions at landing. The lander was sized based on a landing system for the Mars Exploration Rovers (MER) so that the lander would be able to properly orient the helicopter. The landing system for this application was modified so that no airbag would be used, and the lander would have 6 petals (base, top, 4 sides) instead of the 4 petals used on MER. Having more petals allows the helicopter to fit more easily inside the lander and effectively reduces the lander mass and volume. The thickness of the petal was reduced by 20% to account for the lower impact velocity

(3.6 m/s for the helicopter vs. 24 m/s for MER) while still maintaining the structural strength to damp the launch loads and vibrations. Since the gravity on Titan is less than half the gravity on Mars, it is easier for a lander on Titan to orient the vehicle upright; therefore, smaller petal motors are required. The motors used for this lander were estimated as half the MER motor mass of 20 kg. A 30% contingency was added to the final mass of the lander petals. To size the lander petals, different combinations of petal dimensions and attachment angles were run in a MATLAB code to determine a minimum mass model that would fit inside the aeroshell.

Once the lander was designed, an inflatable flotation device was sized to fit around the lander so that the lander could float if it landed in liquid methane. The flotation device material is assumed to be Vectran ( $\rho = 1400 \text{ kg/m}^3$ ) filled with helium. The flotation device was sized using simple buoyancy calculations.

## *2. Option II: Mid-Atmospheric Deployment*

An alternative to the landing option is a mid-atmospheric deployment. In this scenario, the parachute also deploys at Mach 1.1. Then, at an altitude below 36 km, when the heat rate from the descent is less than  $10^{-5} \text{ W/cm}^2$ , pyros will disconnect the helicopter from the heatshield and backshell. The heatshield will be jettisoned as it is no longer needed, allowing the entry to be slowed even further. The backshell will ascend up the parachute riser because the atmosphere underneath is exerting an upward force on it that is greater than the force on the parachute. Therefore, the backshell falls slower than the parachute and rises relative to the parachute risers. At this point, the helicopter is still attached to the parachute and is exposed to the Titan environment. The helicopter needs to be exposed to the environment because the power system operates using Titan's atmosphere. Batteries on the helicopter will provide the initial power to startup the helicopter's engine. After one minute, the turbo expander will be fully functioning and both the backshell and parachute will be released. When the helicopter is a safe distance away from the parachute and backshell, the turbo expander will attach itself to the rotor shaft and start spinning the blades to a high enough rpm so that the helicopter can produce sufficient lift to commence its initial flight into the Titan atmosphere. The EDT summary for this option is shown in Figure 4.



**Figure 4: EDT Schematic for Mid-Atmospheric Deployment Option**

During the two second interval when the helicopter is not attached to the parachute and the turbo expander is not attached to the shaft, autogyration will keep the helicopter in a stable orientation. Autogyration is the occurrence of the helicopter rotor spinning without power due to external forces. In this case, the blades can be oriented at a particular angle of attack so that as the helicopter is descending, the air pushing up on the blades causes them to rotate. This rotation will keep the helicopter stable in its descent through the atmosphere. Many current helicopters have the ability to land unpowered using autogyration.

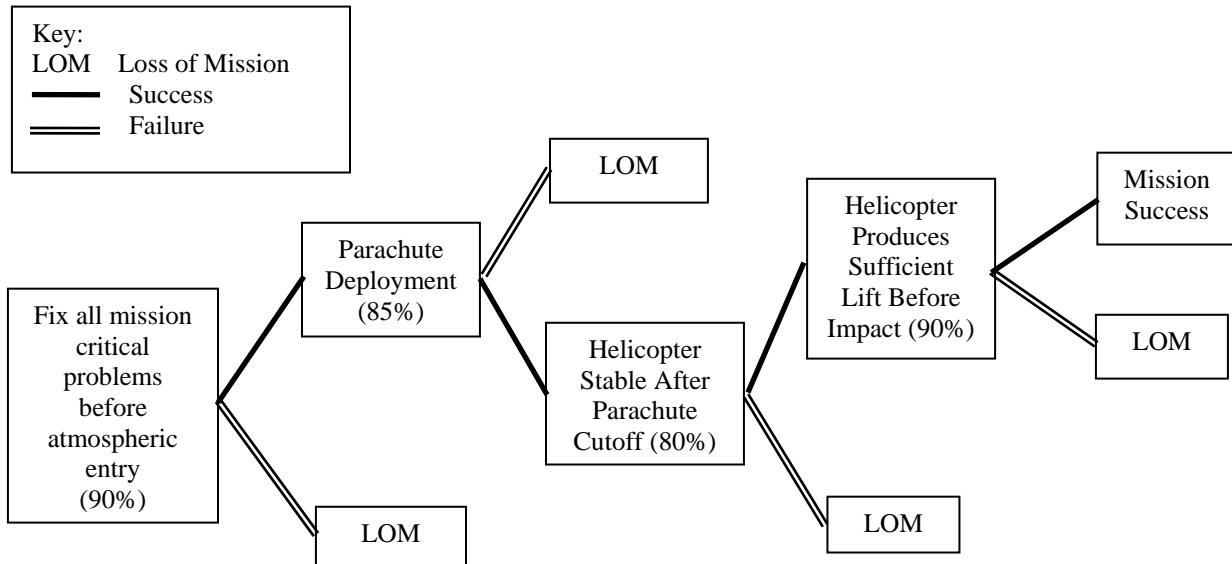
A mid-atmospheric deployment has several advantages over the landing option that allow a number of failure modes to be eliminated. A major advantage is that no complicated landing system is necessary to ensure that the helicopter lands upright on a level surface. By reducing the complexity of a landing system, the risk of mission failure decreases. Also, since a lander system is not necessary, a more massive helicopter could be designed. The helicopter structure does not have to be designed to withstand any impact loads, which could reduce the mass of the helicopter. Also, there is no mass or volume restriction on the helicopter in making the aeroshell buoyant.

There are several disadvantages associated with a mid-atmospheric deployment. First of all, the systems checks performed during the cruise to Titan will have to be sufficient to ensure that the helicopter will operate properly upon entry into Titan. In other words, once the aeroshell enters the atmosphere, there is nothing that can be done to fix a problem with the helicopter before it begins its flight. For example, if the helicopter's attitude determination controls are not functioning properly during entry, they cannot be fixed before the helicopter's maiden flight. If a problem with any system is found shortly before entry, there may not be enough time to fix it before the aeroshell enters the atmosphere.

There is added complexity associated with a mid-atmospheric deployment since the helicopter is trying to fly while falling. The helicopter must be stable when it comes out of the aeroshell.

Also, if a parachute is used, care must be taken to ensure the helicopter rotor does not get tangled in the parachute risers or suspension lines. Although autogyration will be used to keep the helicopter stable, it is not certain whether autogyration will be sufficient enough to stabilize the helicopter if it is oscillating heavily under the parachute.

A diagram showing the failure modes for the mid-atmospheric deployment option is shown in Figure 5 below. As in the previous option, probabilities of success for each failure mode were assigned by the author based on intuition, and should not be taken as absolute numbers.



**Figure 5 Fault Tree for Mid-Atmospheric Deployment Option**

As can be seen from this fault tree, there are four mission critical events that could lead to a loss of mission. The probability for a loss of mission is about 45.3%. This high chance for a loss of mission is because any failure ends in a loss of mission. To decrease the chance for a loss of mission, contingencies should be designed into the model. Comparing Figure 3 and Figure 5 shows that a mid-atmospheric deployment is a much riskier option than landing.

The quantitative analysis for the mid-atmospheric deployment option consisted of inputting the Titan data and parameter values from Table 6 and Table 7 into POST. The data were analyzed to determine an acceptable altitude for the helicopter to exit the aeroshell. It was assumed that the helicopter would be able to produce enough vertical lift if it was falling no faster than 3.5 m/s. To determine the altitude at which the helicopter should be released to ensure a descent rate of less than 3.5 m/s, an analysis was performed that calculated the parachute cutoff altitude needed to achieve various startup velocities. This analysis was repeated for varying parachute diameters to find a less massive parachute. The mathematical process behind the parachute sizing is given in Ref [4].

### III. Results and Discussion

#### A. Option I: Landing

In the landing option, the aeroshell follows a typical velocity profile for a lifting entry (Figure 6). One key output from POST used for the analysis of Option I is the surface velocity. For this trajectory, the velocity at impact was 3.6 m/s. This velocity, the terminal velocity of the system, is relatively slow due to the high density of Titan ( $5.3 \text{ kg/m}^3$  at the surface).<sup>2</sup> The lander is able to withstand the low impact load of about 0.2 Earth g's since it is less than the launch load of roughly 10 Earth g's. Therefore, the lander's structural mass does not need to be increased to withstand the impact load.

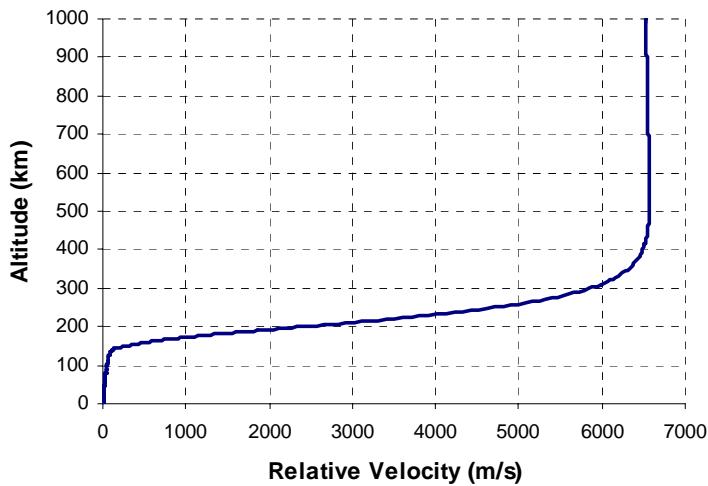
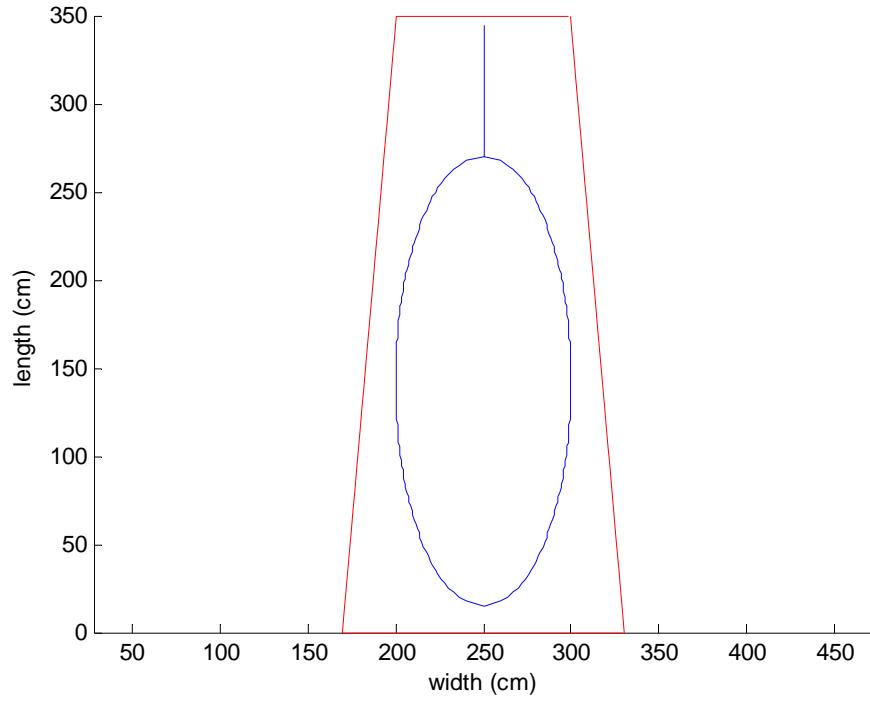


Figure 6: Velocity Profile

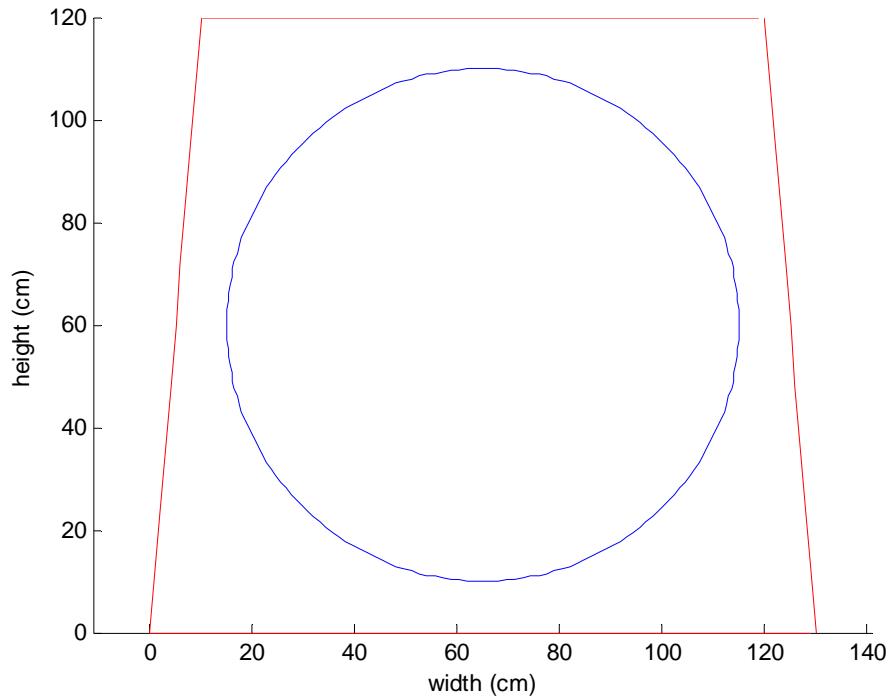
In sizing the landing system, various petal sizes were fitted around each side of the helicopter until an orientation that yielded the minimum mass was found. Adequate space was allotted between the helicopter and the lander for attachments. The result of this analysis for the baseline helicopter is shown in Table 8 and Figure 7 – 9. Side 1 corresponds to the side view of the helicopter, and Side 2 corresponds to the side covering the front view of the helicopter.

Table 8 Petal Mass Breakdown for Baseline Helicopter

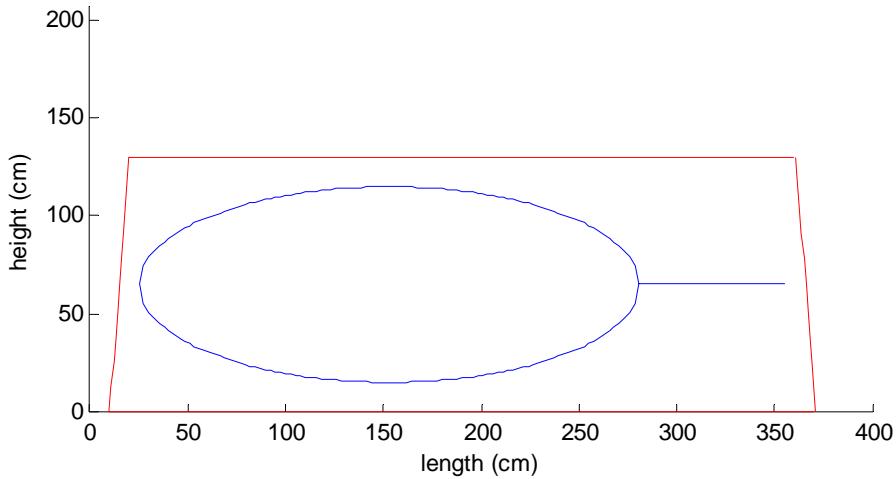
Petal	Area ( $\text{m}^2$ )	Maximum Expected Mass (kg)
Top	4.30	29.1
Base	4.55	40.8
Side 1 ( $\times 2$ )	4.56	30.9
Side 2 ( $\times 2$ )	1.44	9.7
Motor	–	10.0
<b>Total</b>		<b>161.0</b>



**Figure 7 Top View of Baseline Helicopter Inside Lander**



**Figure 8 Front View of Baseline Helicopter Inside Lander**

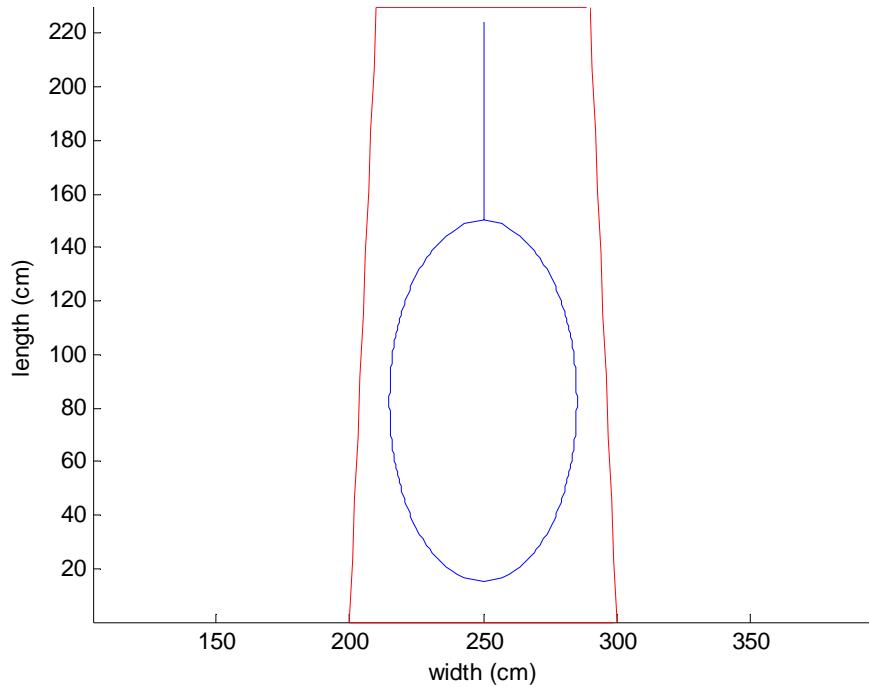


**Figure 9 Side View of Baseline Helicopter Inside Lander**

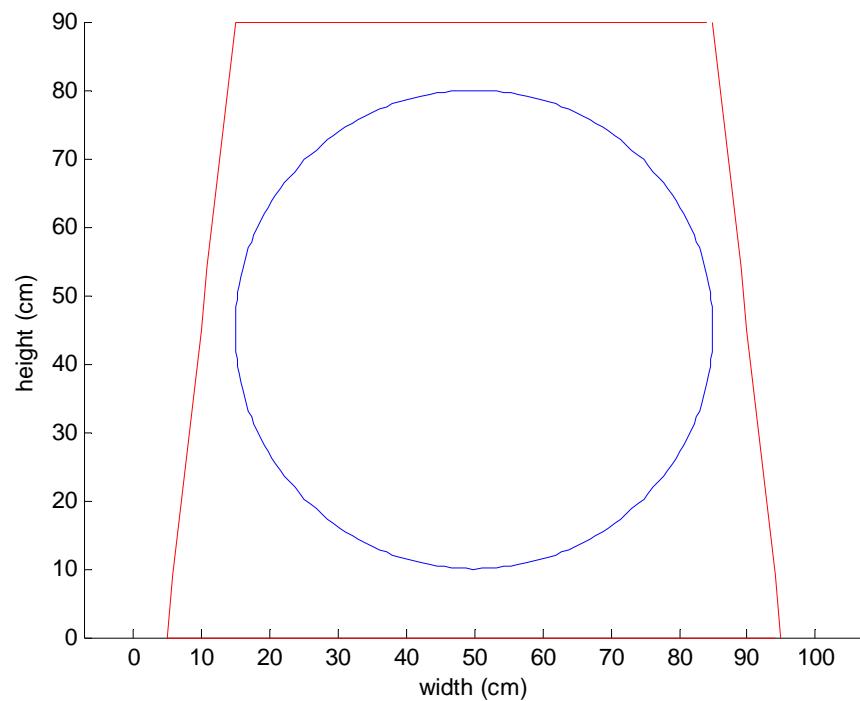
The landing system for the baseline helicopter is much larger than the available 32.5 kg from Table 3. Also, the landing system does not fit inside the aeroshell because its dimensions are too large. Therefore, for the lander option to be feasible for a Titan helicopter, the mission must be reduced so that a smaller helicopter and thus smaller lander can be used. A landing system was sized for the reduced mission helicopter, and is shown below in Table 9 and Figure 10 – 12.

**Table 9 Petal Mass Breakdown for Reduced Mission Helicopter**

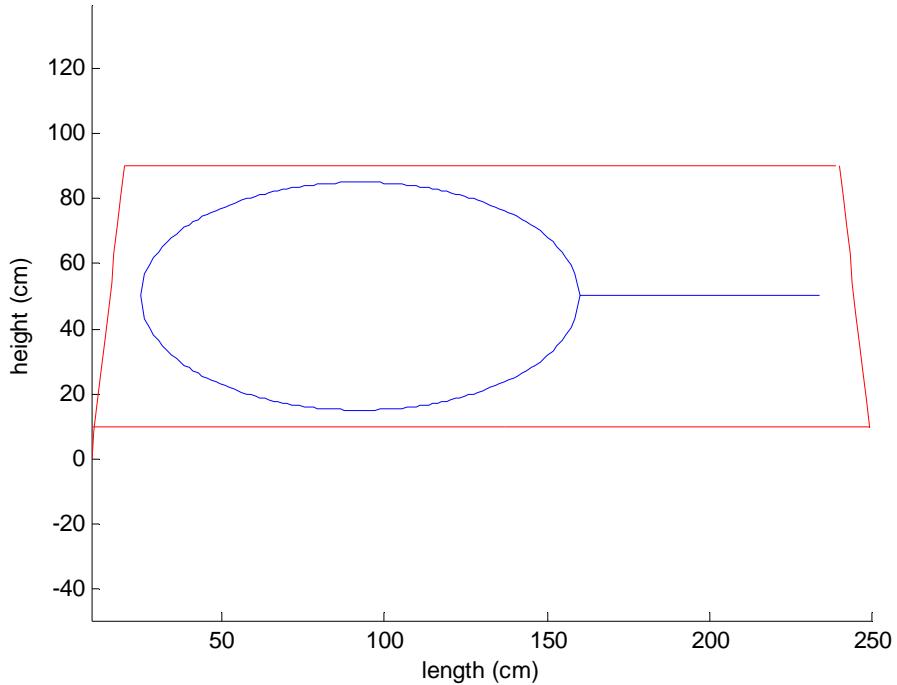
Petal	Area ( $\text{m}^2$ )	Max Expected Mass (kg)
Top	1.96	13.3
Base	2.07	24.0
Side 1 ( $\times 2$ )	1.92	13.0
Side 2 ( $\times 2$ )	0.72	4.9
Motor	–	10.0
<b>Total</b>		<b>83.0</b>



**Figure 10 Top View for Reduced Mission Helicopter Inside Lander**



**Figure 11 Front View of Reduced Mission Helicopter Inside Aeroshell**



**Figure 12 Side View of Reduced Mission Helicopter Inside Aeroshell**

The lander sized for the reduced mission helicopter easily satisfies the lander mass allocation of 138.1 kg given in Table 4. A flotation device must be sized to allow the lander to float in liquid methane. Using buoyancy calculations, the mass breakdown of the flotation system is given in Table 10.

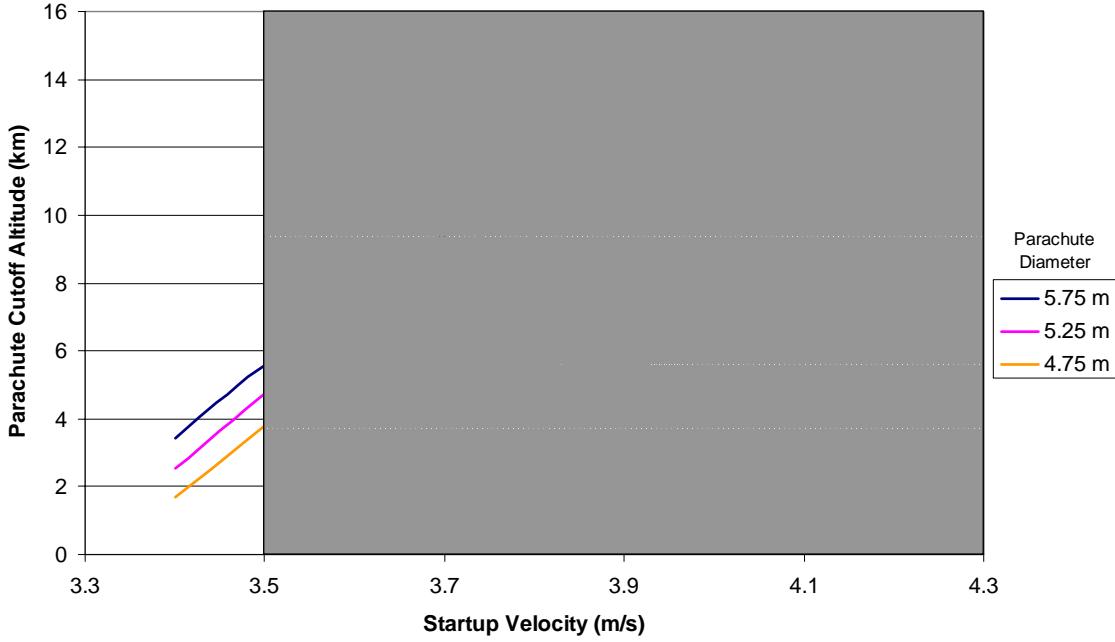
**Table 10 Flotation Device Mass Breakdown**

Flotation Device	Value (kg)
Flotation Material	2.4
Tank	5.3
Gas	1.4
<b>Total</b>	<b>9.1</b>

Adding the total flotation device mass to the lander mass gives a total landing system mass of 92.1 kg, which is still an acceptable value. Therefore, a landing option is feasible with a heavily compromised mission.

## B. Option II: Mid-Atmospheric Deployment

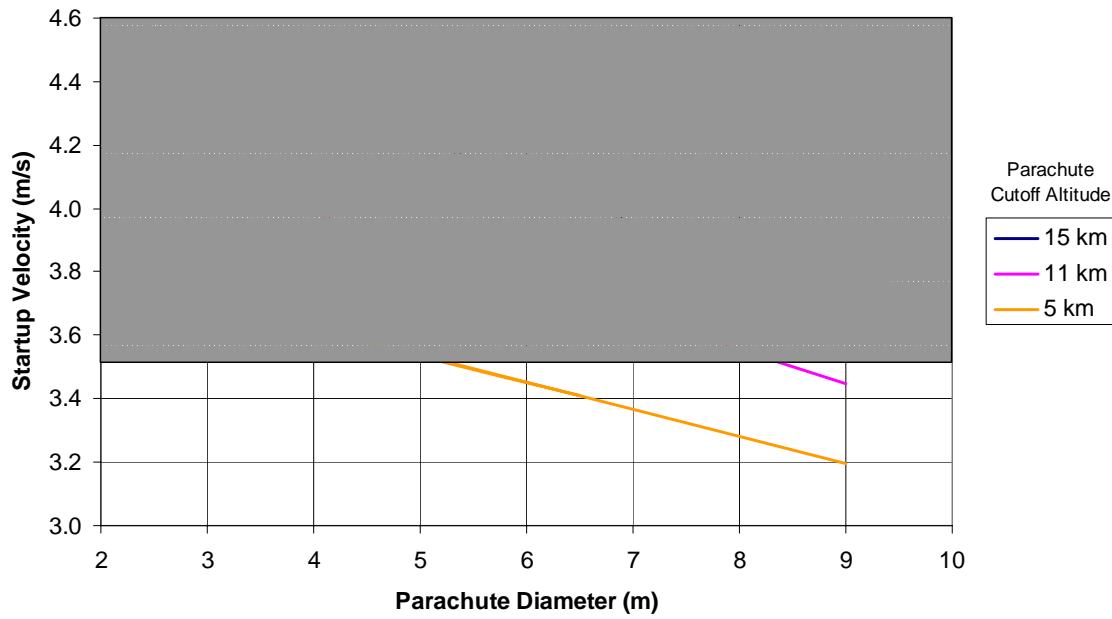
For the mid-atmospheric deployment analysis, variations in parachute diameter and parachute cutoff altitude were analyzed to observe their affect on the helicopter startup velocity (i.e. descent rate 2 seconds after parachute cutoff). The results of this analysis are shown in Figure 13. The shaded portion of this figure represents the infeasible design space where the startup velocity exceeds 3.5 m/s.



**Figure 13 Parachute Cutoff Velocity vs. Startup Velocity**

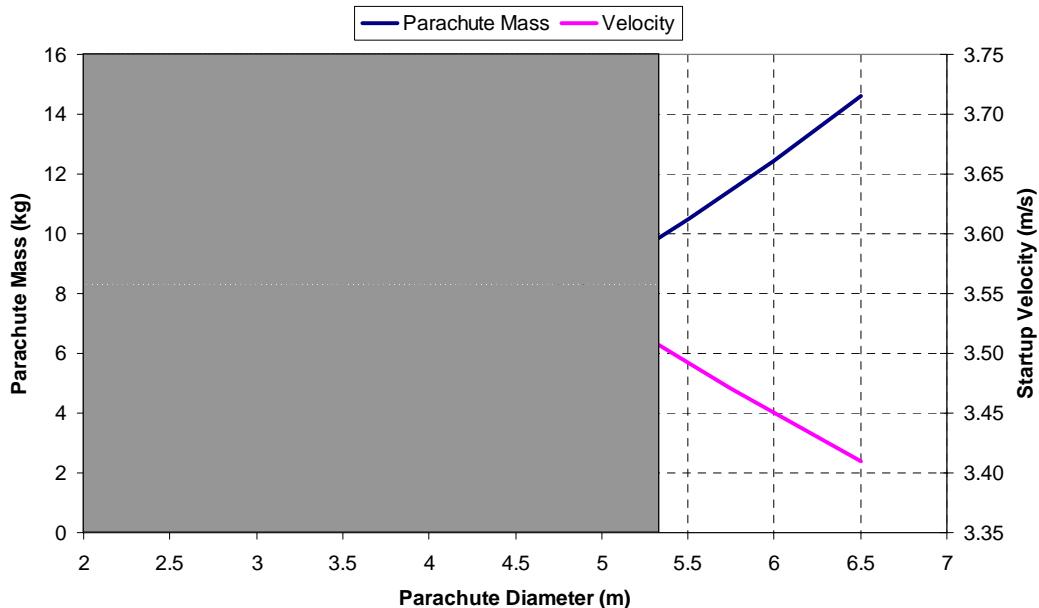
Figure 13 shows that the parachute cutoff altitude increases almost quadratically with the startup velocity. This trend occurs because the atmosphere is denser at lower altitudes, causing a greater drag for the parachute. To most easily obtain the 3.5 m/s startup velocity requirement, we should release the helicopter at the lowest permissible altitude. Releasing the helicopter at a lower altitude has the added benefit of slower winds, which are relatively small at low altitudes on Titan.<sup>5</sup> The limiting factor for the cutoff altitude is the altitude of the highest terrain, which was assumed to be 3 km. Therefore, if the aeroshell is released at 5 km, the helicopter will begin turning the rotor at an altitude of 4.8 km and have more than 10 minutes to produce sufficient lift to hover until it reaches 3 km.

To determine the effect of parachute diameter on the startup velocity, the startup velocity was plotted against varying parachute diameters for different cutoff altitudes. This graph is shown in Figure 14. Once again, the shaded portion represents the infeasible design space where the startup velocity is greater than 3.5 m/s.



**Figure 14 Startup Velocity vs. Parachute Diameter**

Figure 14 shows that the startup velocity decreases linearly with increasing parachute diameter. Therefore, for a given parachute cutoff altitude, the parachute can be sized simply by specifying the desired startup velocity. However, there is a tradeoff here because as the parachute diameter increases, the mass of the parachute increases. Therefore, to find an optimal parachute diameter, the mass of the parachute was plotted for various parachute diameters assuming a parachute cutoff altitude of 5 km (Figure 15). To better determine which parachute diameter to use, the startup velocity was also plotted on this figure.



**Figure 15 Parachute Mass and Startup Velocity for Varying Diameters**

From Figure 15, one can infer that a parachute diameter of 5.43 m is the smallest parachute diameter that can obtain the maximum startup velocity, corresponding to a parachute mass of 10.1 kg. Adding in a factor of safety, the final parachute diameter that will be used is 10% higher, corresponding to a diameter of 5.97 m and a parachute mass of 12.3 kg. Therefore, the parachute required for the helicopter to perform a mid-atmospheric deployment is slightly larger than the parachute required for the NASA LaRC design. Although the helicopter is less massive than the airship, the parachute is larger because of the helicopter's low equilibrium velocity. The additional mass used by this parachute falls well within the allowable mass for the baseline helicopter mission.

The analysis for the two transition to flight methods shows a tradeoff between risk and mission endurance. The mid-atmospheric deployment option is much riskier than the landing option, but allows the helicopter to have a much larger mission endurance. A higher fidelity risk analysis should be conducted to determine a more substantial probability for loss of mission for both transition to flight scenarios. The defining characteristic for the transition to flight method is the mission endurance. Since use of a lander greatly reduced the mission to one that would limit our understanding of Titan, the mid-atmospheric deployment option was determined to be the better transition to flight candidate. This decision is enhanced when one considers that there may not be many chances to explore Titan, so exploring as much of Titan as possible with any given mission is of the utmost importance.

#### IV. Verification

The analysis for each transition to flight method was verified to ensure that the results were accurate. The trajectory analysis for both transition to flight options was calculated using POST, which has been used successfully on numerous atmospheric entry problems.<sup>6</sup> The results from the POST output were compared with those given by NASA LaRC to verify that the input deck contained the appropriate parameters (Appendix A and B).

For the landing option, the MATLAB code (Appendix C) that was created was verified by resizing the MER lander petals. A triangular petal shape was used for the MER petals, and the rover itself was approximated as a cuboid (rectangular box). A lander sizing spreadsheet was created that calculated the mass of the petals given its area. The spreadsheet was verified by accurately sizing the MER lander petals (Appendix D).

The parachute sizing spreadsheet (Appendix E) was verified by resizing the NASA LaRC parachute for the airship. Using the airship mass and equilibrium velocity, the parachute mass was found to be 11.8 kg, about 4 % higher than the value given by NASA LaRC.

## V. Conclusion

The results from the EDT analysis show that the choice in transition to flight method greatly affects the helicopter design space. The analysis showed that using a lander requires a large amount of mass that adversely affects the vehicle design space. Using a lander would require the Titan helicopter be much smaller and able to accomplish only a fraction of its baseline mission, which would reduce the science that could be performed. A viable alternative to using a lander was found. A mid-atmospheric deployment of the helicopter allows the helicopter to be sized to accomplish its baseline mission while eliminating a number of failure modes associated with the landing option. The mid-atmospheric deployment is not without its shortcomings. The main concern with a mid-atmospheric deployment is its high risk and stability using autogyration after the helicopter is released from the parachute. Although autogyration is used on many helicopters on Earth, the ability for autogyration to actually stabilize the helicopter during descent needs to be tested to a high level of fidelity before it is put to use on Titan.

Appendix

## A. POST Input Deck – Landing Option

```

c
heatk(1) = 1, 300000, 1000, /coefficients for Chapman's heating eqn
rhosl = 5.26,      /sea level density for Chapman's heating
c
npc(16) = 1,       / spherical planet (Titan)
npc(30) = 3,       / use enhanced weight model
istepf = 1,        / include all steps in dry weight
nstpl = 1,         / number of lowest step
nstph = 3,         / number of highest step
c
c step weights
c
wstpd(1) = 444.8, / heatshield, backshell, and pallet ring, etc. + parachute
wstpd(2) = 400.0,  / helicopter + lander (landed mass)
c
re = 2575000.0,   / Titan equatorial radius(m)
mu = 8.977276e+12, / Titan gravitational constant (m**3/s**2)
omega = 1.63788e-04, / Titan rotation rate (rad/sec)
go = 1.35,        / weight to mass conversion factor (m/s**2)
c
iguid(1) = 0,      / atmospheric aerodynamic angle guidance
iguid(2) = 0,      / same functional relationship for all angles
iguid(3) = 1,      / use constant term in polynomials for guidance
alppc(1) = 0,
betpc(1) = 0,
bnkpc(1) = 0,
c
c initial conditions
maxtim = 25000.,
dt = 1.0,
time = 0.,
c
c
cccccc initialization using spherical inertial frame cccccccc
veli = 6500,       / inertial velocity (m/s)
azveli = 0.0,       / azimuth angle of inertial velocity vector
gammai = -49.999785, / inertial flight path angle (deg)
gcrad = 3575000., / geocentric radius (Titan atm interface 1000km alt) (in meters)
gclat = 0.0,        / geocentric latitude
long = 0.0,         / planet relative longitude (east of prime meridian)
c
sref = 11.04,       / aero ref area(m**2)
c
monx = 3hasm,6hheatrt,
mony = 6haltito,6haltito,
pinc = 240,         / print increment
prnt(91) = 4hmass,5hxmax1,5hyxmx1,5hxmax2,5hyxmx2,6hdamp1,6diarp1,6dragpt,4hmach,
$
I$tblmlt
$
I$tab
table = 5hprest,1,6haltito,51,1,1,1,
0.00,141900,20000,46220,40000,14100,60000,4190,80000,1770,100000,943,120000,535,140000,315,
160000,191,180000,118,200000,74.2,220000,47.3,240000,30.5,260000,19.9,280000,13.1,300000,8.7,
320000,5.8,340000,3.88,360000,2.6,380000,1.74,400000,1.16,420000,0.769,440000,0.507,460000,
0.332,480000,0.215,500000,0.139,520000,0.0885,540000,0.0563,560000,0.0353,580000,0.0221,600000,
```

```

0.0147,620000,0.0095,640000,0.00631,660000,0.00422,680000,0.00286,700000,0.00196,720000,0.00132,
740000,0.000962,760000,0.000685,780000,0.000493,800000,0.000354,820000,0.000263,840000,0.000194,
860000,0.000144,880000,0.000108,900000,0.0000811,920000,0.0000613,940000,0.0000464,960000,
0.0000353,980000,0.0000207,1000000,0.0000206,
ixtrp = 0,0,0,
$
l$tab
table = 5hatemt,1,6haltito,51,1,1,1,
0.0092,1.20000,74.8,40000,70.66,60000,76.87,80000,123.61,100000,142.06,120000,151,140000,158.55,
160000,163.77,180000,167.3,200000,170.48,220000,173.21,240000,175.42,260000,177.02,280000,177.97,
300000,178.79,320000,177.63,340000,176.21,360000,173.85,380000,170.6,400000,166.61,420000,162.08,
440000,157.19,460000,152.18,480000,147.28,500000,142.78,520000,139.01,540000,136.32,560000,135.05,
580000,135.33,600000,136.65,620000,138.79,640000,141.52,660000,144,680000,147.99,700000,151.42,
720000,154.84,740000,158.15,760000,161.27,780000,164.37,800000,166.79,820000,169.09,840000,171.05,
860000,172.65,880000,173.85,900000,174.63,920000,174.98,940000,175,960000,175,980000,175,1000000,175,
ixtrp = 0,0,0,
$
c
c aerodynamic tables - ballistic
c
l$tab
table = 3hcdt,0, 1.0000,
$
l$tab
table = 3hclt,0,0.0,
endphs = 1,
$
c
ccccccccccccccccc EVENT 20 - Intersect Titan atmosphere cccccccccccccccccc
l$genda
c
event = 20,
critr = 6haltito,
value = 1000000,
npc(1) = 0,      / end calculation of orbital elements
pinc = 1,
nstpl = 1,
endphs = 1,
$
c
ccccccccccccccccccccc EVENT 30 - BEGIN CHUTE DEPLOYMENT cccccccccccccccccc
l$genda
c
event = 30,1,
critr = 'mach',
value = 1.1,
npc(32) = 1,    / beginning of chute deployment
diamp = 0.,   / initial diameter of chute (m)
parif = 3.,   / parachute inflation factor (inflation rate = velap/parif)
$
c
l$tblmlt
$
l$tab
table = 'cdp1t', 0, 0.525,

```

```

endphs = 1,
$
c
cccccccccccccccccc EVENT 40 - END MAIN CHUTE INFLATION ccccccccccccccccccc
l$genda
c
event = 40,1,
critr = 'diamp1',
value = 5.75,
parif(1) = 0,
endphs = 1,
$
c
cccccccccccccccccc EVENT 50 - DROP HEAT SHIELD ccccccccccccccccccc
cl$genda
c
c event = 50,1,
c critr = 6haltito,
c value = 15000,
c nstpl = 3,
c endphs = 1,
c $
c
cccccccccc EVENT 60 - DROP HEAT SHIELD, BACKSHELL, & PARACHUTE cccccccccc
l$genda

event = 60,1,
critr = 6haltito,
value = 2000,
diamp = 0.,
nstpl = 2,
endphs = 1,
$
c
cccccccccccccccccc EVENT 100 - SURFACE IMPACT ccccccccccccccccccc
l$genda
c
event = 100,
critr = 6haltito,
value = 0,
endphs = 1,
endprb = 1,
endjob = 1,
$

```

## B. POST Input Deck – Mid-Atmospheric Deployment

```

heatk(1) = 1, 300000, 1000, /coefficients for Chapman's heating eqn
rhosl = 5.26,      /sea level density for Chapman's heating
c
npc(16) = 1,       / spherical planet (Titan)
npc(30) = 3,       / use enhanced weight model
istepf = 1,        / include all steps in dry weight
nstpl = 1,         / number of lowest step
nstph = 3,         / number of highest step
c
c step weights
c
wstpd(1) = 335.1, / heatshield and pallet ring, etc.
wstpd(2) = 110.6,  / backshell + parachute
wstpd(3) = 399.1,  / helicopter (landed mass)
c
re = 2575000.0,   / Titan equatorial radius(m)
mu = 8.977276e+12, / Titan gravitational constant (m**3/s**2)
omega = 1.63788e-04, / Titan rotation rate (rad/sec)
go = 1.35,         / weight to mass conversion factor (m/s**2)
c
iguid(1) = 0,      / atmospheric aerodynamic angle guidance
iguid(2) = 0,      / same functional relationship for all angles
iguid(3) = 1,      / use constant term in polynomials for guidance
alppc(1) = 0,
betpc(1) = 0,
bnkpc(1) = 0,
c
c initial conditions
maxtim = 25000.,
dt = 1.0,
time = 0.,
c
c
cccccc initialization using spherical inertial frame cccccccc
veli = 6500,       / inertial velocity (m/s)
azveli = 0.0,       / azimuth angle of inertial velocity vector
gammai = -49.999785, / inertial flight path angle (deg)
gcrad = 3575000.,  / geocentric radius (Titan atm interface 1000km alt) (in meters)
gclat = 0.0,        / geocentric latitude
long = 0.0,         / planet relative longitude (east of prime meridian)
c
sref = 11.045,     / aero ref area(m**2)
c
monx = 3hasm,6hheatrt,
mony = 6haltito,6haltito,
pinc = 240,         / print increment
prnt(91) = 4hmass,5hxmax1,5hyxmx1,5hxmax2,5hyxmx2,6hdamp1,6diarp1,6dragpt,4hmach,
$
l$tblmlt
$
l$tab
table = 5hprest,1,6haltito,51,1,1,1,
0.00,141900,20000,46220,40000,14100,60000,4190,80000,1770,100000,943,120000,535,140000,315,
160000,191,180000,118,200000,74.2,220000,47.3,240000,30.5,260000,19.9,280000,13.1,300000,8.7,
320000,5.8,340000,3.88,360000,2.6,380000,1.74,400000,1.16,420000,0.769,440000,0.507,460000,
0.332,480000,0.215,500000,0.139,520000,0.0885,540000,0.0563,560000,0.0353,580000,0.0221,600000,

```

```

0.0147,620000,0.0095,640000,0.00631,660000,0.00422,680000,0.00286,700000,0.00196,720000,0.00132,
740000,0.000962,760000,0.000685,780000,0.000493,800000,0.000354,820000,0.000263,840000,0.000194,
860000,0.000144,880000,0.000108,900000,0.0000811,920000,0.0000613,940000,0.0000464,960000,
0.0000353,980000,0.0000207,1000000,0.0000206,
ixtrp = 0,0,0,
$
l$tab
table = 5hatemt,1,6haltito,51,1,1,1,
0.0092,1.20000,74.8,40000,70.66,60000,76.87,80000,123.61,100000,142.06,120000,151,140000,158.55,
160000,163.77,180000,167.3,200000,170.48,220000,173.21,240000,175.42,260000,177.02,280000,177.97,
300000,178.79,320000,177.63,340000,176.21,360000,173.85,380000,170.6,400000,166.61,420000,162.08,
440000,157.19,460000,152.18,480000,147.28,500000,142.78,520000,139.01,540000,136.32,560000,135.05,
580000,135.33,600000,136.65,620000,138.79,640000,141.52,660000,144,680000,147.99,700000,151.42,
720000,154.84,740000,158.15,760000,161.27,780000,164.37,800000,166.79,820000,169.09,840000,171.05,
860000,172.65,880000,173.85,900000,174.63,920000,174.98,940000,175,960000,175,980000,175,1000000,175,
ixtrp = 0,0,0,
$
c
c aerodynamic tables - ballistic
c
l$tab
table = 3hcdt,0, 1.460,
$
l$tab
table = 3hcld,0,0.365,
endphs = 1,
$
c
ccccccccccccccccc EVENT 20 - Intersect Titan atmosphere cccccccccccccccccc
l$genda
c
event = 20,
critr = 'altito',
value = 1000000,
npc(1) = 0,      / end calculation of orbital elements
pinc = 1,
nstpl = 1,
endphs = 1,
$
c
ccccccccccccccccc EVENT 30 - BEGIN CHUTE DEPLOYMENT cccccccccccccccccc
l$genda
c
event = 30,
critr = 'mach',
value = 1.1,
npc(32) = 1,    / beginning of chute deployment
diamp = 0., / initial diameter of chute (m)
parif = 3., / parachute inflation factor (inflation rate = velap/parif)
$
c
l$tblmlt
$
l$tab
table = 'cdp1t', 0, 0.525,

```

```

endphs = 1,
$
c
cccccccccccccccccc EVENT 40 - END MAIN CHUTE INFLATION cccccccccccccccccccc
l$genda
c
event = 40,
critr = 'diamp1',
value = 5.97,
parif(1) = 0,
endphs = 1,
$
c
cccccccccccccccccc EVENT 50 - DROP HEAT SHIELD cccccccccccccccccccccccc
l$genda
c
event = 50,
critr = 'altito',
value = 5000,
nstpl = 3,
endphs = 1,
$
c
ccccccccccccccccc EVENT 60 - DROP BACKSHELL & PARACHUTE cccccccccccccccc
l$genda
c drop backshell and parachute one minute after dropping heat shield
event = 60,
critr = 'times',
value = 60,
diamp = 0.,
nstpl = 2,
endphs = 1,
$
c
ccccccccccccccccc EVENT 70 - COMMENCE FLIGHT cccccccccccccccccccc
l$genda
c print out data 2 seconds after parachute cutoff
event = 70,
critr = 'times',
value = 2,
endphs = 1,
$
c
ccccccccccccccccc EVENT 100 - SURFACE IMPACT cccccccccccccccccccc
l$genda
c
event = 100,
critr = 'altito',
value = 0,
endphs = 1,
endprb = 1,
endjob = 1,
$
```

## C. Lander MATLAB Code

```
% Ravi Prakash
% EDL Special Topics
% Lander Sizing Program
% This program will size the lander petals for the Titan helicopter. It
% was first sized for the MER petals to verify the code.

clear all
close all
clc

% Dimensions (cm)
% Helicopter (fuselage)
height = 70;
length = 135;
width = 70;
tail = 75;

% Rover Dimensions (cm)
% height = 150;
% length = 160;
% width = 230;

% Make rectangle (Rover)
% for i = 1:(length+1)
%     x1(i) = 200;
%     y1(i) = (i-1)+15;
%     x2(i) = x1(i) + width;
%     y2(i) = y1(i);
% end
% for i = 1:(width+1)
%     x3(i) = (i-1)+200;
%     y3(i) = 15;
%     x4(i) = (i-1)+200;
%     y4(i) = length+15;
% end

% Make helicopter fuselage
elliptical_height = height;
elliptical_length = length;
elliptical_diameter = width;

% Make your elliptical cross-section (side view)
elliptical_lengths = linspace(-elliptical_length/2, elliptical_length/2);
elliptical_heights1 = sqrt((1 - (elliptical_lengths.^2 ./ (elliptical_length/2)^2)) .* (elliptical_height/2).^2);
elliptical_heights2 = -sqrt((1 - (elliptical_lengths.^2 ./ (elliptical_length/2)^2)) .* (elliptical_height/2).^2);
elliptical_lengths = [elliptical_lengths -elliptical_lengths];
elliptical_heights = [elliptical_heights1 elliptical_heights2];

% Make your elliptical cross-section (front view)
r_ellipse=elliptical_diameter/2;
i=0;
for theta=[0:pi/100:2*pi];
    i=i+1;
    plot_ellipse_x(i)=r_ellipse*(cos(theta));
    plot_ellipse_y(i)=r_ellipse*(sin(theta));
```

```

end

% Inputs
base_start = 200;
top_start = 210;
top_start_y = 230;

% Make trapezoid
% Base
Base_length = 500 - 2*base_start;
for i = 1:Base_length
    x5(i) = base_start+(i-1);
    y5(i) = 0;
end

% Top
Top_length = 500 - 2*top_start;
for i = 1:Top_length
    x8(i) = top_start+(i-1);
    y8(i) = top_start_y;
end

% Side2
line_slope1 = top_start_y/(top_start - base_start);
counter = 0;
for i = base_start:top_start
    counter = counter + 1;
    x6(counter) = i;
    y6(counter) = line_slope1*(x6(counter) - base_start);
end
line_slope2 = top_start_y/((top_start+Top_length) - (base_start+Base_length));
counter = 0;
for i = (top_start+Top_length):(base_start+Base_length)
    counter = counter + 1;
    x7(counter) = i;
    y7(counter) = line_slope2*(x7(counter) - (base_start+Base_length));
end

% make triangle - used in rover verification
% for i = 1:(width+400)
%     x5(i) = (i-1);
%     y5(i) = 0;
% end
% for i = 1:316
%     x6(i) = i-1;
%     y6(i) = x6(i);
%     x7(i) = i+314;
%     y7(i) = 630 - x7(i);
% end

hold on
% plot rectangle (Rover)
% plot(x1,y1)
% plot(x2,y2)
% plot(x3,y3)
% plot(x4,y4)

```

```

% Top View
elliptical_heights2 = elliptical_heights + base_start+Base_length/2;
elliptical_lengths2 = elliptical_lengths + length/2 + 15;
plot(elliptical_heights2,elliptical_lengths2,'b')

% Make tail
tail_start = max(elliptical_lengths2);
for i = 1:tail
    tail_draw_x(i) = 250;
    tail_draw_y(i) = tail_start - 1 + i;
end
plot(tail_draw_x, tail_draw_y)

% plot trapezoid (Top View)
plot(x5,y5, 'r')
plot(x6,y6, 'r')
plot(x7,y7, 'r')
plot(x8,y8, 'r')

% plot triangle
% plot(x5,y5,'r')
% plot(x6,y6,'r')
% plot(x7,y7,'r')

xlabel('width (cm)')
ylabel('length (cm)')
axis equal

hold off

%%%%% SIDE VIEW %%%%%%
base_start = 10;
top_start = 20;
top_start_y = height+20;

Base_length = length+30+tail;
for i = 1:Base_length
    x53(i) = base_start+(i-1);
    y53(i) = 10;
end

% Top
Top_length = 50-2*top_start+length;
for i = 1:Top_length+tail
    x83(i) = top_start+(i-1);
    y83(i) = top_start_y;
end

% Side2
line_slope1 = top_start_y/(top_start - base_start);
counter = 0;
for i = base_start:top_start
    counter = counter + 1;
    x63(counter) = i;
    y63(counter) = line_slope1*(x63(counter) - base_start);

```

```

end
line_slope2 = max(y83)/(max(x83) - max(x53));
counter = 0;
for i = (top_start+Top_length+tail):(base_start+Base_length)
    counter = counter + 1;
    x73(counter) = i;
    y73(counter) = line_slope2*(x73(counter) - (base_start+Base_length));
end
figure

hold on

elliptical_heights3 = elliptical_heights + r_ellipse+15;
elliptical_lengths3 = elliptical_lengths + length/2+25;
plot(elliptical_lengths3,elliptical_heights3,'b')

% Make tail
tail_start = max(elliptical_lengths3);
for i = 1:tail
    tail_draw_x(i) = tail_start - 1 + i;
    tail_draw_y(i) = 50;
end
plot(tail_draw_x, tail_draw_y)

% plot trapezoid (Top View)
plot(x53,y53, 'r')
plot(x63,y63, 'r')
plot(x73,y73, 'r')
plot(x83,y83, 'r')

xlabel('length (cm)')
ylabel('height (cm)')
%axis([0 400 0 150])
axis equal

hold off

%%%%% Plot Front View %%%%%%
base_start = 5;
top_start = 15;
top_start_y = 90;

plot_ellipse_x = plot_ellipse_x+r_ellipse+15;
plot_ellipse_y = plot_ellipse_y+r_ellipse+10;
figure
hold on
plot(plot_ellipse_x, plot_ellipse_y,'b')
xlabel('width (cm)')
ylabel('height (cm)')
axis equal

% Make trapezoid
% Base
Base_length2 = 20 + width;
for i = 1:Base_length2
    x52(i) = base_start+(i-1);

```

```

y52(i) = 0;
end

% Top
Top_length = 30 - 2*top_start + width;
for i = 1:Top_length
    x82(i) = top_start+(i-1);
    y82(i) = top_start_y;
end

% Side2
line_slope1 = top_start_y/(top_start - base_start);
counter = 0;
for i = base_start:top_start
    counter = counter + 1;
    x62(counter) = i;
    y62(counter) = line_slope1*(x62(counter) - base_start);
end
line_slope2 = top_start_y/((top_start+Top_length) - (base_start+Base_length2));
counter = 0;
for i = (top_start+Top_length):(base_start+Base_length2)
    counter = counter + 1;
    x72(counter) = i;
    y72(counter) = line_slope2*(x72(counter) - (base_start+Base_length2));
end

% plot trapezoid (Front View)
plot(x52,y52, 'r')
plot(x62,y62, 'r')
plot(x72,y72, 'r')
plot(x82,y82, 'r')

```

## D. Lander Sizing Spreadsheet

Contingency Margin	30%	30%	
Vehicle Mass	kg	174	127.84
Lander Mass (no airbag)	kg	250	161.04
Max Expected Lander Mass	kg		209.36
Max Expected with Margin	kg		272.16
<b>Dimensions</b>			
Height	m	1.5	1
Length	m	1.6	3.56
Width	m	2.3	1
Surface Gravity	m/s <sup>2</sup>	3.73	1.35
Landing Velocity	m/s	24	3.6
Launch Loads	g's	10	10
Number of petals	-	4	6
Base Petal Area	m <sup>2</sup>	9.2	4.55
Side Petals 1 Area (each)	m <sup>2</sup>	6	4.56
Side Petals 2 Area (each)	m <sup>2</sup>		1.44
Top Petal Area	m <sup>2</sup>	0	4.30
Material Density * Thickness	kg/m <sup>2</sup>	8.46	6.76
Max with Margin			
Base Petal	kg	77.79	40.78
Side Petals 1 (each)	kg	50.74	30.85
Side Petals 2 (each)	kg		9.74
Top Petal	kg	0.00	29.09
Motors	kg	20	10
<b>Total Lander Mass</b>	kg	250	<b>161.04</b>
			<b>272.16</b>

## E. Parachute Sizing Spreadsheet

<b>Titan Helicopter Parachute Sizing</b>		
Material Density	0.30	kg/m <sup>2</sup>
C <sub>D0</sub>	0.525	
g <sub>0</sub>	1.35	m/s <sup>2</sup>
Entry Mass	593.3	kg
Entry Weight	800.96	N
Equilibrium Velocity	11.86	m/s
density (@ 5 km)	4.351	kg/m <sup>3</sup>
Nominal Diameter	5.97	m
Surface Area	27.99	m <sup>2</sup>
Parachute Mass	8.48	kg
Parachute Mass with Margin	11.21	kg
Parachute Lines, etc.	1.12	kg
<b>Total Parachute</b>	<b>12.33</b>	<b>kg</b>

## **References**

- 1 "Titan Explorer: Orbiter and Aerial Platform," NASA Langley Research Center, 2003.
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