

AN OPTIMIZED TRAJECTORY FOR A TWO-STAGE, SURFACE TO ORBIT TITAN LAUNCH VEHICLE

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As part of a NIAC funded Titan sample return mission, NASA GRC's Compass Team has investigated a two-stage, in-situ propellant, launch vehicle design. This paper presents a proposed trajectory for the vehicle and mission of interest. This trajectory is optimally solved to balance drag losses in the denser atmosphere along with gravity losses accumulated during vehicle ascent to select an optimal path from Titan's surface to a parking orbit. The resulting trajectory is characterized by a slow, vertical climb to an altitude above the densest part of the atmosphere followed by a vehicle pitch-over and climb to orbital insertion. The resulting ΔV is 3.96 km/s.

INTRODUCTION

As an outer solar system moon with a dense atmosphere and hydrocarbon seas, Titan is unique as a celestial body and of significant scientific interest. Titan sample return missions are complex, with large ΔV and propellant requirements and are difficult to plan and achieve. Eliminating the need to bring return propellants by using propellants gathered at Titan would significantly reduce the landed mass requirement for a Titan sample return mission and could provide for a feasible mission. This paper details the nominal surface to orbit trajectory of the vehicle designed by the Compass Team as part of a sample return mission that uses in-situ propellants to make a Titan sample return mission feasible.¹ The launch vehicle (LV) designed by the Compass Team is illustrated in Figure 1.

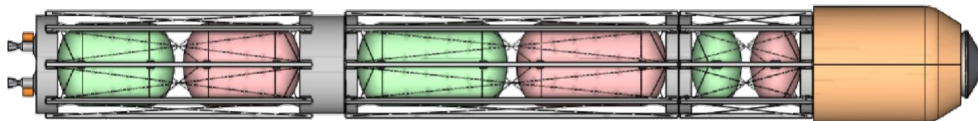


Figure 1: CAD Representation of the Titan LV.

The atmospheric density of Titan is significant and at its surface is 4.3 times denser than that of Earth's. Titan's acceleration due to gravity ($g_{acc} = 1.352\text{m/s}^2$) is only 13% of that on Earth. The thick atmosphere and low gravity of Titan is a unique environment for launch vehicle (LV) analysis.

The nominal trajectory for the vehicle proposed by the Compass Team is for a two stage to orbit (TSTO) vehicle and was optimized using Optimal Trajectory by Implicit Simulation (OTIS v4.0) software. The vehicle is configured with a drag profile, propulsion system and masses that are representative of the Compass return vehicle design. The optimizer chooses a flight path within the constraints and design parameters of the problem to minimize drag losses in the lower portion of the atmosphere and balances them against gravity loss accumulated through the ascent. The resulting trajectory is characterized by an initial, long vertical climb through the lower portion of the atmosphere followed by a pitch-over and final ascent to orbit insertion.

The resulting trajectory begins nearly vertical, with an initial thrust to weight ratio (for weight calculated at Titan gravity) of about 2 to reduce drag losses through the lower atmosphere. This initial thrust to weight ratio is maintained at or near thrust/weight ($T/W = 2$) by optimally throttling

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through the majority of the first stage ascent while the vehicle is deep in Titan's atmosphere. The initial ascent is very slow as the OTIS optimization reduces the throttle to minimize drag losses. Typical velocity for the vehicle during the first stage of the ascent is below 100 m/s and continues to an altitude greater than 30 km. Above the denser part of the atmosphere, the engines throttle up and the vehicle begins a slow pitch-over maneuver. Much of the pitch-over actually occurs at an altitude closer to 40 km. The launch fairing is jettisoned at 150 km altitude, where drag is negligible. The overall trajectory has a 72-minute ascent, comprising 22 minutes of thrust, followed by a 49-minute coast, and then a 0.2 km/s circularization burn to insert into a 1000 km circular Titan orbit. The total launch ΔV to Titan orbit is 3.9 km/s, of which the first stage accounts for roughly 25% of the total ΔV and about 45% of the total propellant.

In addition to the nominal trajectory, this paper examines the solution's sensitivity to drag area on the overall trajectory and ΔV . Also presented is a preliminary investigation of ΔV requirement for a high-altitude launch above the denser portion of the atmosphere.

APPROACH

This section details top-level requirements for the Titan LV, a corresponding trajectory for achieving design and mission objectives, the numerical tool used and development of associated vehicle sub-system models.

Objective and Top-Level Titan Launch Vehicle Study Requirements

The objective for the Titan LV is to deliver a maximum payload to a specified orbit. Among the top-level requirements for the study is the development of an optimized trajectory for a representative Compass design LV. This vehicle must launch from the Titan surface with a known, fixed mass and deliver an optimally maximum payload to a 1000 km circular orbit. The resulting ΔV s, stage propellant loads and final payload mass to orbit were communicated to the Compass Team for further incorporation into their LV design. A Titan LV Concept of Operations table is shown in Appendix A, Table A.1. Details on the final Compass LV design and the Earth to Titan round trip legs of the integrated mission have been presented in a previous paper.¹

Two Stage to Orbit (TSTO) Vehicle Design

Typically, to achieve a surface to orbit launch a single- or multi-stage LV design is employed. Single stage to orbit (SSTO) designs offer simplicity, and potentially cost savings, over multi-staged approaches. While SSTO launch vehicles are often considered for celestial bodies with relatively low gravity like Titan; however, Titan's very thick atmosphere suggests that vehicle staging offers advantages not achievable with a SSTO. This study's Titan LV trajectory, based on the Compass design for this subset of the integrated mission, is a TSTO vehicle. LV staging is a well-known approach to lower mission propellant requirements by mitigating the mass penalty associated with carrying "dead mass" to orbit. For the Titan LV application, the TSTO approach also adds the ability to tune each vehicle stage for its operating environment. In particular, the first stage of the proposed vehicle delivers a sufficiently high thrust level to initiate launch ascent albeit at the expense of propellant mass due to engine count and lower specific impulse (Isp). The second stage offers a higher Isp at the expense of thrust level during that portion of the ascent where thrust requirements are lower. The TSTO LV burns out after orbit insertion with a third, in-space, stage being part of the TSTO LV's payload system.

TSTO Ascent Trajectory Design

The ascent flight profile for the TSTO design is relatively simple but unlike traditional launch vehicle designs for Earth, this ascent does not use a continuous burn from the surface to orbit insertion. Instead, the trajectory is designed to take advantage of the relatively low gravity on Titan, and associated lower gravity loss terms, compared to that for Earth launches. This approach

is like that proposed for the Mars Ascent Vehicle (MAV) project.² One key difference between Titan and Mars, however, is the presence of the thick Titan atmosphere; so, unlike the MAV trajectory where the LV pitched over at a relatively low altitude in the atmosphere, the first burn of the Titan ascent flight is designed to minimize drag loss by allowing the vehicle to climb much higher before it pitches over and heads down range. This burn-coast-burn approach is also believed to be like the ascent trajectory proposed in a similar sample return mission proposed by another team in a 2010 study.³

The overall burn-coast-burn, TSTO trajectory is depicted schematically in Figure 2 and begins with first stage ignition on Titan's surface. The LV then climbs under a vertical attitude hold to an altitude of 0.03 to 1.5 km, designed to restrict the vehicle from prematurely pitching over near the launch pad. Due to the very dense lower atmosphere on Titan, it never appears optimal to perform a pitch-over maneuver at a lower altitude making this attitude hold constraint largely unnecessary; the constraint was left in as a precaution. After the initial climb under a vertical attitude hold, the vehicle was permitted to continue its ascent under an optimal attitude performing a short pitch-over to generate down range velocity. Pitch-over maneuver altitude, angle and rate were all optimally determined. Following pitch-over, the aerodynamic angles are ramped to zero and held through maximum dynamic pressure (Q_{max}) to mitigate aerodynamic bending loads. At the Q_{max} altitude, the vehicle's attitude controls were released to allow the remainder of the flight ascent to be flown under fully time-varying, optimal controls (pitch only) to an altitude where the propulsion system is terminated. Following the propulsive ascent portion of flight there is a long coast towards apoapsis. Near apoapsis, the propulsion system is re-ignited to perform a short burn to insert the LV into the desired final, 1000 km circular orbit.

The initial portion of the ascent, from launch to the coast, is performed by two stages: the first portion of the initial powered ascent is handled by the first LV stage. At an optimal altitude, constrained to meet a Compass design requirement that the two stages carry roughly equal propellant, the first stage burns out and is jettisoned in favor of the second stage which completes the initial portion of the ascent and performs the final orbit insertion burn. The initial burn of the second stage is also briefly interrupted at an altitude of 150 km where a small payload fairing is jettisoned. The 150 km altitude for payload fairing jettison was chosen as a simplification of a more realistic low dynamic pressure criterion for this maneuver; however, it is sufficiently high to conservatively satisfy most future dynamic pressure considerations.

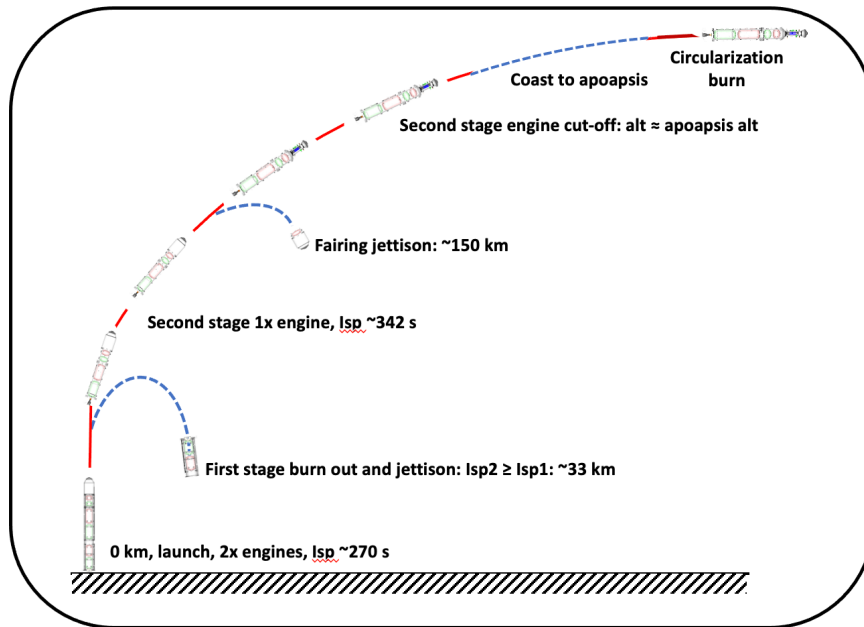


Figure 2. Conceptual Schematic of the TSTO, Burn-Coast-Burn Ascent Profile

Numerical Tool

The numerical software tool used to simulate and optimize the Titan LV flight for this study is Optimal Trajectories by Implicit Simulation (OTIS v.4).⁴ OTIS has been previously used for a variety of vehicle trajectory performance studies. OTIS’ applications include launch vehicles, aircraft, and interplanetary spacecraft. OTIS is primarily a three-degree of freedom (3DOF) simulation tool with optimization of a user defined objective function. All solutions for this study used OTIS’s interface to the well-known Sparse Nonlinear Optimizer (SNOPT).

Primary Objective

The primary objective of the mission is to deliver a maximum payload based on a fixed initial mass of 3800 kg launched from the surface of Titan. This initial mass is representative of the Compass Team’s LV design and includes proposed in-situ manufactured propellant while the vehicle is on Titan’s surface.

To simulate and optimize the TSTO trajectory, sub-system models were developed and implemented. The development of these sub-systems and their associated key assumptions are detailed in the following sections.

Titan Atmosphere Model

Titan’s atmosphere is more than four times denser than that of the Earth near its surface and remains very dense extending to nearly a 1000 km above its surface. This density of Titan’s atmosphere presents a challenge to any LV and thus requiring careful consideration of atmospheric drag. Since OTIS does not come equipped with a default atmosphere for Titan, one was developed for this study. The data used to develop the atmosphere model are presented in Figure 3.⁵

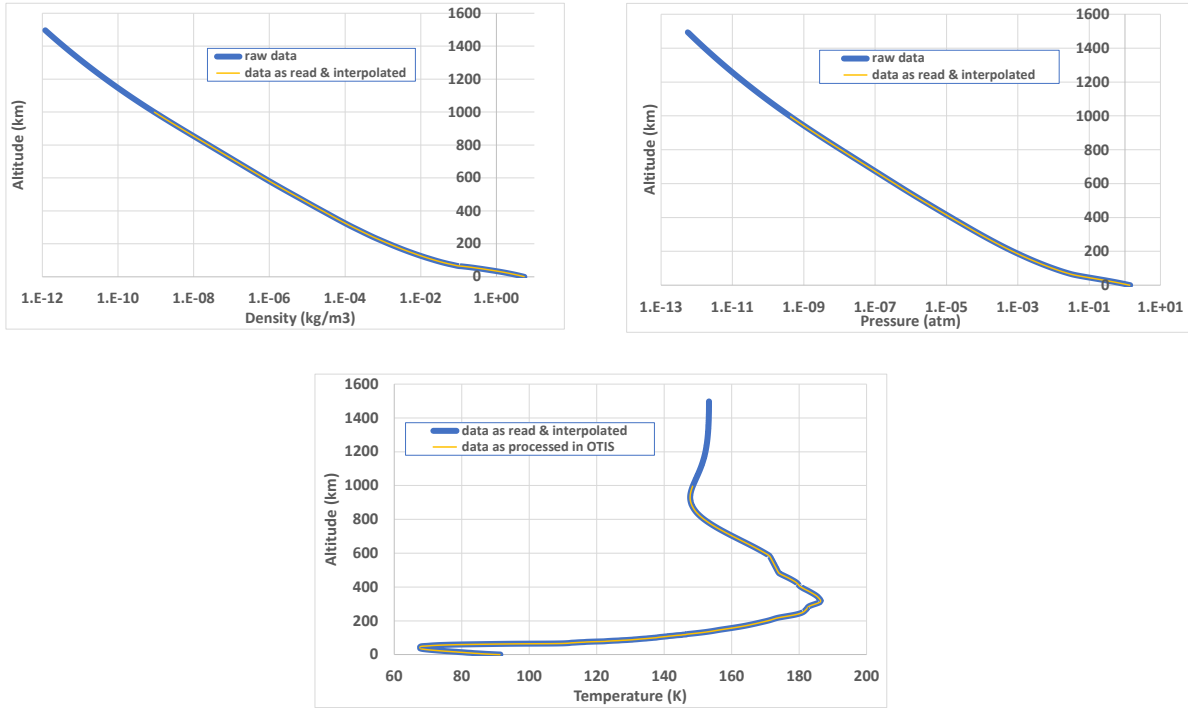


Figure 3. Vertical Profile of Atmospheric Density (kg/m³), Pressure (atm) and Temperature (K) Used to Develop the Atmosphere Model in OTIS.

Aerodynamic Model

A Mach dependent aerodynamic coefficient of drag (C_d) was obtained and used to compute the drag force acting on the LV during its ascent. For simplicity, aerodynamic lift (C_l) and cross coefficients (C_c) are not considered.

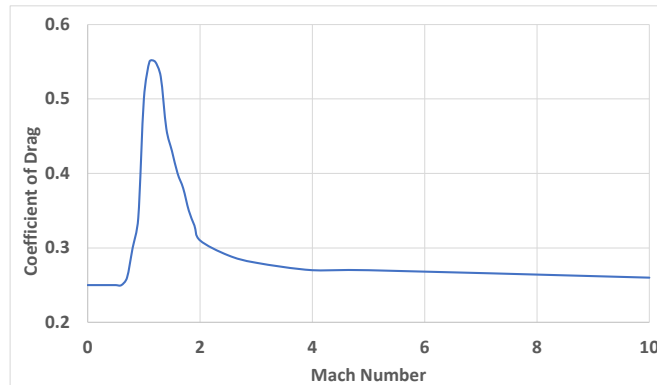


Figure 4. C_d as a Function of Mach Used in the OTIS Drag Model.

The impact of Titan's atmosphere is included in the OTIS simulation of the Titan LV trajectory via drag force calculated based on the C_d profile in Figure 4 along with supplied Titan atmospheric data. The cross-sectional drag area (A_{ref}) from the Compass design is $A_{ref} = 1.23 \text{ m}^2$; this corresponds to a design diameter $d = 1.25 \text{ m}$. This diameter was held constant throughout the study while varying LV stage lengths to create enough volume to accommodate the necessary propellant.¹

Titan Central Body and Gravitational Model

Gravitational and central body parameters for Titan from The Navigation and Ancillary Information Facility (NAIF) were used to define the central celestial body's gravity model. The ascent flight was modeled as a two-body problem with Titan as the central body and the LV as the secondary. The simulation is configured with a zonal gravity model (J terms up through J_4). Gravitational perturbations from third bodies (e.g., Saturn) were not included.

Propulsion Model

The Titan sample return LV's first and second stage engines consume LO_2/LCH_4 propellants and are based on an open gas generator cycle with an overall oxidizer/fuel (O/F) ratio of 3.0. The Compass Team's design utilizes common components in the LV's propulsion system so that the first and second stage engines have identical powerheads, thrust chambers, and regeneratively cooled 20:1 area ratio for the nozzles. The second stage engine, however, has both an additional uncooled nozzle extension and a deployable nozzle skirt to increase its overall area ratio to 120:1. To obtain adequate performance at Titan surface conditions, a peak chamber pressure of 103 bar (1,500 psi) is selected which allows the first stage engine to provide an Isp of 270 s at Titan's surface and the second stage engine to develop 342 s of vacuum Isp with the larger second stage nozzle. The performance curves of these two engine configurations are plotted in Figure 5 and show that their Isp curves intersect at a Titan altitude of ~ 35 km and an Isp of 311 s. This crossover of the Isp curves is used to trigger staging in the trajectory analysis.

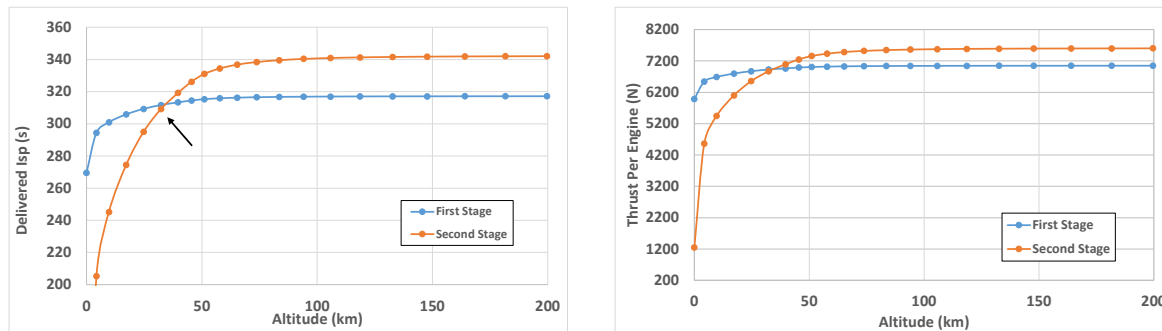


Figure 5. Delivered Isp and Thrust Per Engine Plotted as a Function of Altitude. The Target Isp Criteria for Staging is Indicated with a Black Arrow on the Isp Plot.

The propulsion data presented in Figure 5 were supplied to OTIS as a function of altitude. It should be noted that the propulsion curves presented above, although a function of atmospheric pressure, are implemented in OTIS as a function of altitude for clarity and ease of implementation; either implementation is equivalent in OTIS.

RESULTS

This section presents the results of the analysis used to supply ΔV requirements to the Compass Team for the integrated LV design. Results are presented for the nominal trajectory, a sensitivity analysis to A_{ref} and a preliminary analysis examining the potential benefits of launching from an altitude above Titan's lower atmosphere.

Nominal Trajectory

Plots of the Titan LV's altitude, velocity, mass, and dynamic pressure as a function of time are presented in Figure 6. For reference, the locations of key events are labeled in these plots. Also presented in Figure 6 is a plot of altitude as a function of flight path angle (FPA.)

The ascent trajectory is characterized by a long, slow vertical climb through the densest part of Titan's atmosphere. During the initial, nearly vertical climb, an optimal throttle is used to maintain an approximate $T/W \approx 2$ as shown in Figure 7. Doing so balances drag and gravity losses and results in typical velocities below 100 m/s for the vertical rise. Once the vehicle reaches an optimal altitude of ~ 33 km, the first stage burns out and is jettisoned. The second stage then continues to complete the first burn arc. The stages are sized using a mass fraction of the total propellant consumed; the first stage mass jettison for the Compass design is 193 kg. This jettison can be seen as the mass delta at ~ 6 -minutes in Figure 6.

The second LV stage continues the nearly vertical, slow climb of the first stage until it reaches an altitude where the pitch-over occurs. As seen in the altitude plot of FPA in Figure 6, the bulk of this pitch-over maneuver occurs around an altitude of 40 km which is considered very high and not typical in launch profiles on celestial bodies with less dense atmospheres. Once pitched over, the vehicle increases down range distance and velocity while continuing its climb to an altitude of 335 km and a velocity of 1.75 km/s. At 335 km, the second stage engine shuts down and the vehicle begins a long coasting phase. At the altitude of engine cut-off, the radius of apogee (R_a) has been raised to nearly that of the final target orbit, as would be expected. The velocity achieved at engine cut-off is more than the velocity required for a 1000 km, circular orbit, of 1.56 km/s. The vehicle loses velocity (trading for altitude) as it coasts to the altitude required for a brief circularization burn. The final flight phase for the trajectory is a relatively short circularizing burn where the vehicle inserts into the final circular target orbit at an altitude of ~ 1000 km. It should be noted that, for numerical optimization ease, an altitude band was allowed for the final orbital altitude. The achieved altitude of the final orbit in this study is ~ 1012 km.

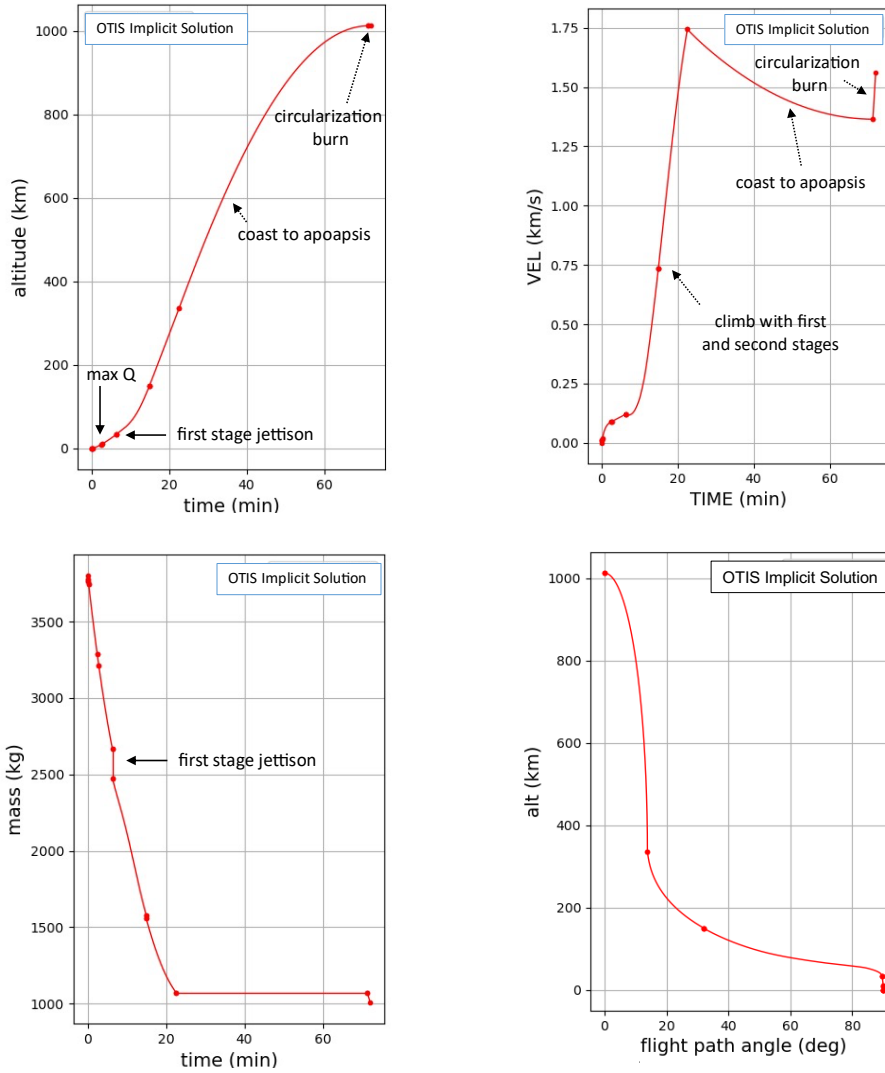


Figure 6. Time History of Altitude, Velocity, Mass, and Dynamic Pressure and Flight Path Angle Plotted as a Function of Altitude. For Reference, OTIS Phase Terminations are Indicated with Solid Points.

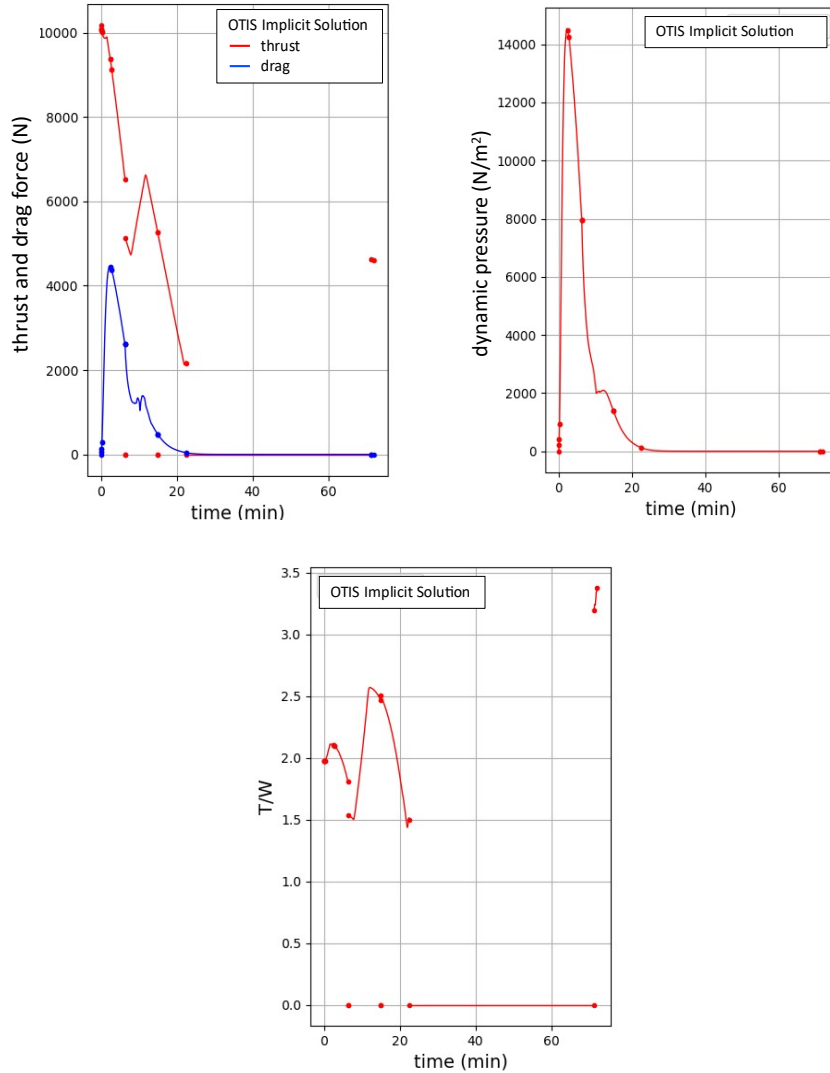


Figure 7. Time History Profiles for Thrust, Drag Forces and Thrust to Weight (T/W) (in Terms of Titan-g). For Reference, OTIS Phases are Indicated with Solid Points and Selected Key Phases, and Events are Labeled.

Time histories of thrust and drag force in the first plot in Figure 7 show the high thrust of the combined engines of nearly 10000 N required to achieve the optimal $T/W \approx 2$ and then the effect of the throttle to reduce thrust and maintain that approximate T/W as the vehicle expends propellant. Most of the ascent is relatively gentle with T/W only reaching 3.4 during the brief circularization burn. Dynamic pressure peaks at approximately 14488 N/m^2 at an altitude of 10.8 km when drag forces also peak at approximately 4500 N.

Mass, ΔV and Propellant Usage During the Nominal Ascent

Table 1. Summary of Propellant, Flight Phase Durations, and ΔV for the Nominal Trajectory.

Overall Summary			
Gross Lift-off Mass	3800 (kg)		
initial T/W	2.0		
Burn Out Mass	1009 (kg)		
Total ΔV	3.964 (km/s)	Total Propellant	2577 (kg)
Mass Summary by Stage			
	First Stage	Second Stage	
Initial Mass	3800 (kg)	2472 (kg)	
Burn Out Mass	2665 (kg)	1009 (kg)	altitude (km)
First Stage Drop Mass	-193 (kg)		32.98 (km)
Final Mass	2472 (kg)	1009 (kg)	
	*second stage burn out mass includes a 22.5kg fairing drop		
ΔV and Propellant Summary by Stage			
	First Stage	Second Stage	Total
ΔV	1.04 km/s	2.93 km/s	3.96 km/s
Propellant	1136 kg	1441 kg	2577 kg
Time of Flight, ΔV and Propellant Summary by Flight Phase			
	Flight Time	ΔV	Propellant
Climb	22.6 (min)	3.766 (km/s)	2516 (kg)
Coast to Apoapsis	48.8 (min)	-- na --	-- na --
Circularization Burn	0.7 (min)	0.198 (km/s)	61 (kg)
Total:	72.1 (min)	3.964 (km/s)	2577 (kg)

A summary of mass, propellant usage and ΔV required for the flight ascent are presented in Table 1. This table breaks down mass, propellant and ΔV by first and second stage and by climb, coast, and circularization burn.

The initial, fixed mass of 3800 kg is launched from the surface of Titan and a final burn out mass of 1009 kg is delivered to the final orbit. The entire ascent lasts 72 minutes, requires a ΔV of 3.964 km/s and consumes 2577 kg of propellant. The 72-minute ascent, is comprised of 23 minutes of thrust, followed by a 49-minute coast, and then a 44 second, 0.2 km/s circularization burn to insert into a 1000 km circular Titan orbit.

The first stage consumes 1136 kg of propellant and delivers 1.04 km/s of the total ΔV . The second stage consumes 1441 kg of propellant and delivers 2.93 km/s of the total ΔV (note that the mass delta in the table includes a 22 kg payload fairing that is jettisoned). The inefficiency of the slow vertical climb through the lowest portion of the Titan atmosphere manifests itself in a disproportionate ΔV split, favoring the second stage while there is a nearly equal split in propellant, largely resulting from early drag losses and LV stage Isp differences

Trajectory Sensitivity to Drag Area

An analysis was performed to see how the overall ΔV reacts to changes in the reference drag area. The results of this analysis are presented in Figure 8. This analysis was conducted early in the Compass design cycle with a slightly different version of the vehicle's design with a higher base ΔV than the 3.96 km/s for the final Compass design; however, the trends and sensitivities should be representative. The results are presented below.

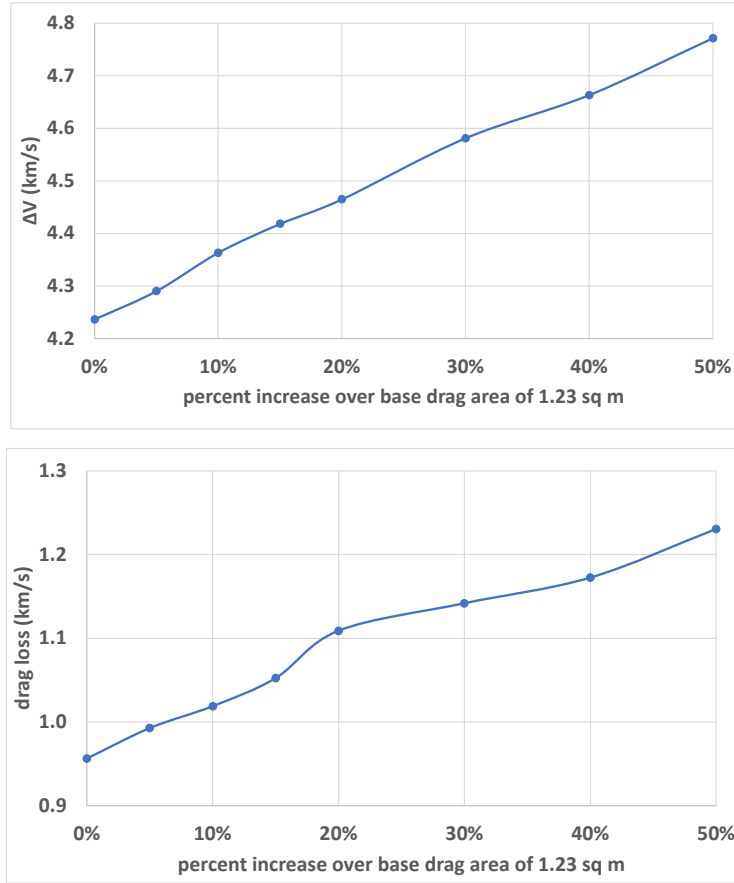


Figure 8. Total ΔV and Drag Loss ΔV Component Plotted Against % Increase in Drag Reference Area.

The analysis was performed by scaling the drag reference area for an optimal trajectory using a scaling factor that represents a % increase over the base area and forms the x-axis in Figure 8. As in the final Compass design, the base reference area of the earlier design is $A_{ref} = 1.23 \text{ m}^2$ which corresponds to a cylindrical diameter of 1.25 m. The trends in Figure 8 are obvious that increasing the drag area increases drag losses and results in an overall higher, total ΔV . The slope of the nearly linear relationship of the ΔV plot is interesting where modest increases in the design reference area results in relatively large changes in drag loss and total ΔV .

As an example of the overall sensitivity, scaling the base drag area by 50%, from 1.23 m^2 ($d = 1.25 \text{ m}$) to 1.85 m^2 ($d = 1.53 \text{ m}$) adds nearly 600 m/s to the overall ΔV . The increase is directly reflected in the plot of drag losses which exhibit the same trend. Over the range of drag areas considered in the analysis, the results can be generalized as: for every 1% increase in drag area the resulting ΔV increased nearly 12 m/s. These results are not surprising given the dense atmosphere of Titan and indicate that great care must be taken when designing a vehicle intended to launch from its surface.

High Altitude Launch of a Single Stage to Orbit LV

The results from the nominal trajectory and the drag loss sensitivity analysis indicate that launching from the surface of Titan is costly in terms of ΔV and propellant. These two factors also contribute to the overall height of the total vehicle stack as the fuel required to climb through the

atmosphere must be accommodated in a rather small cross-sectional stage to keep drag losses as low as possible.

It is intriguing to consider eliminating the first stage of the proposed LV and directly launch the upper stage from altitudes above the lower Titan atmosphere. While it is beyond the scope of this study to determine the type of high-altitude launch platform to be used (drone, aircraft, balloon...), a preliminary analysis can be performed on a SSTO (i.e., upper stage) version of the proposed LV to evaluate the potential ΔV and propellant savings.

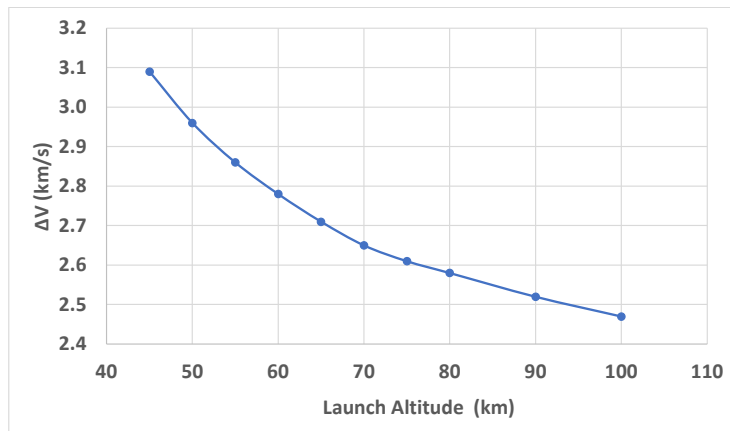


Figure 9. ΔV for Launches at Various Altitudes.

The SSTO version of the vehicle above is configured with the second stage propulsion data presented in Figure 5. The initial mass for the high-altitude launch vehicle is fixed at 1500 kg with an overall objective to maximize delivered mass to a 1000 km circular orbit. All other data, such as atmospheric and aerodynamic, are the same as those presented for the nominal trajectory.

The high-altitude launch is initiated with the vehicle in a horizontal orientation and dropped for 5 seconds to allow an altitude separation to build from the launch platform. The remainder of the flight profile is like that of the surface launched vehicle except for lack of any attitude holds, allowing the vehicle to pitch up and immediately climb in altitude. All previous first stage considerations, e.g., constraints and jettison events, are eliminated for this particular analysis. Once nose up, the vehicle climbs to an orbital state where the R_a is near that of the final orbit, coasts and then re-ignites the engine to circularize the final orbit at the desired 1000 km altitude.

The results show a significant savings for launching at increasingly higher altitudes with a nearly 0.8 to 1.4 km/s reduction factor in overall ΔV for the simulated range of altitudes. While interesting, caution must be exercised when comparing the results from this analysis to those from the base nominal trajectory presented earlier in this paper due to the differences in the vehicles and their flight profiles. An alternative approach for this analysis would, for example, configure a SSTO, high-altitude vehicle to match the delivered mass from the surface launched LV to the same final orbit and subsequently minimize the initial SSTO mass and should be considered in any future work.

SUMMARY AND CONCLUSIONS

Titan's dense atmosphere is a challenge when it comes to designing an LV and trajectory which departs from the surface. The density of the atmosphere creates a significant drag, and this behavior persists high (>30-40 km) into the atmosphere. Trajectory design does benefit from Titan's lower gravity (~13% of Earth's). A trajectory for the Titan sample return mission proposed by the Compass Team optimally navigates the ascent flight, resulting in a unique trajectory characterized

by an initial high altitude, slow ascent through the densest portion of the lower atmosphere before the vehicle pitches over and continues a more traditional ascent profile (Figure 3). The ascent profile proposed for the Compass Team design optimally satisfies mass and flight constraints as proposed in the study. The ascent utilizes a burn-coast-burn strategy to conserve fuel and lower overall ΔV , requiring 3.96 km/s to complete its launch ascent to final orbit insertion. The LV design, and associated trajectory, also employ the strategy of vehicle staging, utilizing a TSTO rocket design to mitigate mass penalties and to take advantage of differing propulsion characteristics for lower and higher flight regimes.

The nominal TSTO ΔV and propellant splits between vehicle stages reveal that the first stage is responsible for approximately 35% of the total ΔV while consuming nearly 45% of the total propellant. This occurs as the optimal path through the lower atmosphere best balances gravity losses against drag losses by climbing above the lower atmosphere while throttling back the engine to mitigate drag losses with lower velocity. The total ΔV of 3.96 km/s is higher than the ΔV reported by Donahue for a Titan ascent.³ The ascent ΔV reported by Donahue was on the order of 3.31 km/s.³ At first, this appears to be a significant mismatch in ΔV of nearly 600 km/s; however, the results presented in Donahue's work may not include the circularization burn included in the Compass design. If that difference is taken into consideration, the results compare to within 10%, a difference which could be attributed to other modeling differences in the approaches and most likely, differences in the atmospheric and aerodynamic drag models.

The highly dependent relationship of total ΔV , and propellant consumption, with choices in reference drag area indicates that small changes in drag area can result in large differences in ΔV required to complete the ascent flight. This sensitivity needs to be considered when designing any vehicle that launches from the surface of Titan and care must be taken to manage the drag profile. The aerodynamic advantage of designing a vehicle with a low drag profile must be balanced against the complexity of designing a tall vehicle stack to accommodate the required propellant.

The inefficiency of the initial ascent (and most of the first stage of the proposed vehicle) is manifest in many of the results presented in this paper. The initial climb and first stage appear to serve very little function in the overall ascent other than to get above Titan's lower atmosphere with as little loss as possible. The initial ascent adds altitude to the profile with little velocity, let alone down range velocity, required to insert into a stable orbit. Given that the first stage consumes a disproportionate amount of propellant for its contribution to the goal of final orbit insertion, it also adds considerable height to the overall vehicle stack. It's intriguing to consider removing the first stage all together and launch a smaller, single stage, vehicle akin to the upper stage of the TSTO LV from an altitude above the densest portion of the Titan atmosphere. A preliminary analysis, examining high altitude launch scenarios, demonstrates the potential ΔV and propellant savings and may be worth considering in future designs. How to achieve the initial launch altitude above the lower atmosphere is beyond the scope of this study; however, high-altitude platforms that use the density of Titan's atmosphere as an advantage such as drones, winged aircraft or balloons may be worth considering. Of course, when considering high-altitude launches, the benefits of saving propellant and ΔV by replacing the first stage would need to be balanced against the added complexity of this alternate scenario.

This study demonstrates that a TSTO launch vehicle, designed with a burn-coast-burn ascent profile, is feasible and does provide ΔV and propellant requirements that are consistent with the masses representative of the LV design presented by the Compass Team. While the results of this study are for a specific flight profile of a specific LV design, the results should also be relevant for other, similar vehicle designs. While the ascent profile and results presented here seem reasonable, other ascent profiles and designs may be able to drive down ΔV and propellant requirements and should be investigated.

ACKNOWLEDGMENTS

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APPENDIX A: CONCEPT OF OPERATIONS

Table A.1. Titan LV Concept of Operations Table: Sequence of Events with Pertinent Vehicle and Mission Information.

OTIS Phase	Ending Condition	Steering (all in plane)	Propulsion (thrust & Isp table lookup)	Throttle	Comments
launch and vertical hold	optimal altitude = [30 to 1500 m]	vertical hold	maximum initial thrust = 12.4kN & Isp = 270 s	time varying optimal between 25 and 100%	
pitch over	optimal flight path angle = [75 to 89.9°]	linear pitch			
ramp to zero aero angle	$\Delta t = 5$ sec	linear ramp down			aerodynamic angles = 0 at end of phase
burn to maximum dyanmic pressure	dynamic pressure maximum	aero ang = 0			
burn to first stage jettison	isp: second stage \geq first stage	optimal steering (pitch)	thrust ~ 6.2kN & Isp = 342s		constrained to an altitude range = [30-35 km]
first stage jettison	--				$\Delta t = 0$ s, Δm scaled by propellant
second stage burn to low dynamic pressure	altitude ≥ 150 km				
fairing jettison	--				$\Delta t = 0$ s, $\Delta m = 22$ kg (fixed)
second stage burn to engine cut off	apoapsis 1000 km				
coast to apoapsis	altitude \approx apoapsis altitude				
circularization burn	state = 1000 km circular			final state ≈ 1000 km circular	

APPENDIX B: GLOSSARY

Table B.1. Glossary of Terms.

FPA	=	Flight Path Angle
LV	=	Launch Vehicle
MAV	=	Mars Ascent Vehicle
NAIF	=	The Navigation and Ancillary Information Facility
OTIS	=	Optimal Trajectory by Implicit Simulation
SSTO	=	Sparse Number Optimizer
SNOPT	=	Single Stage to Orbit
TSTO	=	Two Stage to Orbit
3-DOF	=	Three-Degree of Freedom
A_{ref}	=	Cross-sectional Area
C_d, C_l, C_c	=	Coefficient of Drag, Lift, and Cross-component
ΔV	=	Delta-v
g_{acc}	=	Acceleration Due to Gravity
Isp	=	Specific Impulse
O/F	=	Oxidizer to Fuel Ratio
Q_{max}	=	Maximum Dynamic Pressure
T/W	=	Thrust to Weight Ratio

REFERENCES

- ¹ G.A. Landis, S.R. Oleson, E.R. Turnbull, R.D. Lorenz, D.A. Smith, T. Packard, J.Z. Gyekenyesi, A.J. Colozza and J.E. Fittje. "Mission Incredible: A Titan Sample Return Using In-Situ Propellants," AIAA 2022-1570. AIAA SCITECH 2022 Forum. January 2022.
- ² I.J. Dux, J.A. Huwaldt, R.S. McKamey and J.W. Dankanich, "Mars Ascent Vehicle Gross Lift-off Mass Sensitivities for Robotic Mars Sample Return", NASA/TM-2011-216968, 2001.
- ³ B. Donahue, "Titan Sample Return Mission Concept.", 57th JANNAF Propulsion Meeting, Colorado Springs, CO, 2010
- ⁴ S.W. Paris, J.P. Riehl, W. Sjaaw and R. Falck, Optimal Trajectories by Implicit Simulation: OTIS. Version OTIS 4, Vols. I to IV, Export Controlled International Traffic in Arms Regulations Document, 2008.
- ⁵ J.H. Waite, J. Bell, R.D. Lorenz, R. Achterberg and F.M. Flasar, "A model of variability in Titan's atmospheric structure." Planetary and Space Science, Vol. 86, 2013, pp.45-56., 2013.