An Optimized Trajectory for a Two-Stage, Surface-to-Orbit Titan Launch Vehicle

David Smith
NASA GRC/LSM0, HX5, LLC

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Titan Launch Vehicle: Talk Outline

- Titan Sample Return Mission, Overview, Background and Motivation
- Approach
  - Vehicle design (TSTO)
  - Trajectory design
  - Key GR&A and Design Constraints
- Launch Vehicle Model Development
  - Central Body Characteristics for Titan
  - Atmosphere Data and Model
  - Aerodynamics Model
  - Propulsion Model
- Results
  - ΔV, Propellant and Mass Summary
  - Trajectory Details/Plots
- Trades:
  - Impact of Varying Drag
  - High-altitude Launch
- Summary Conclusions & Future Work

Titan Launch Vehicle: Sample Return Mission, Background and Motivation

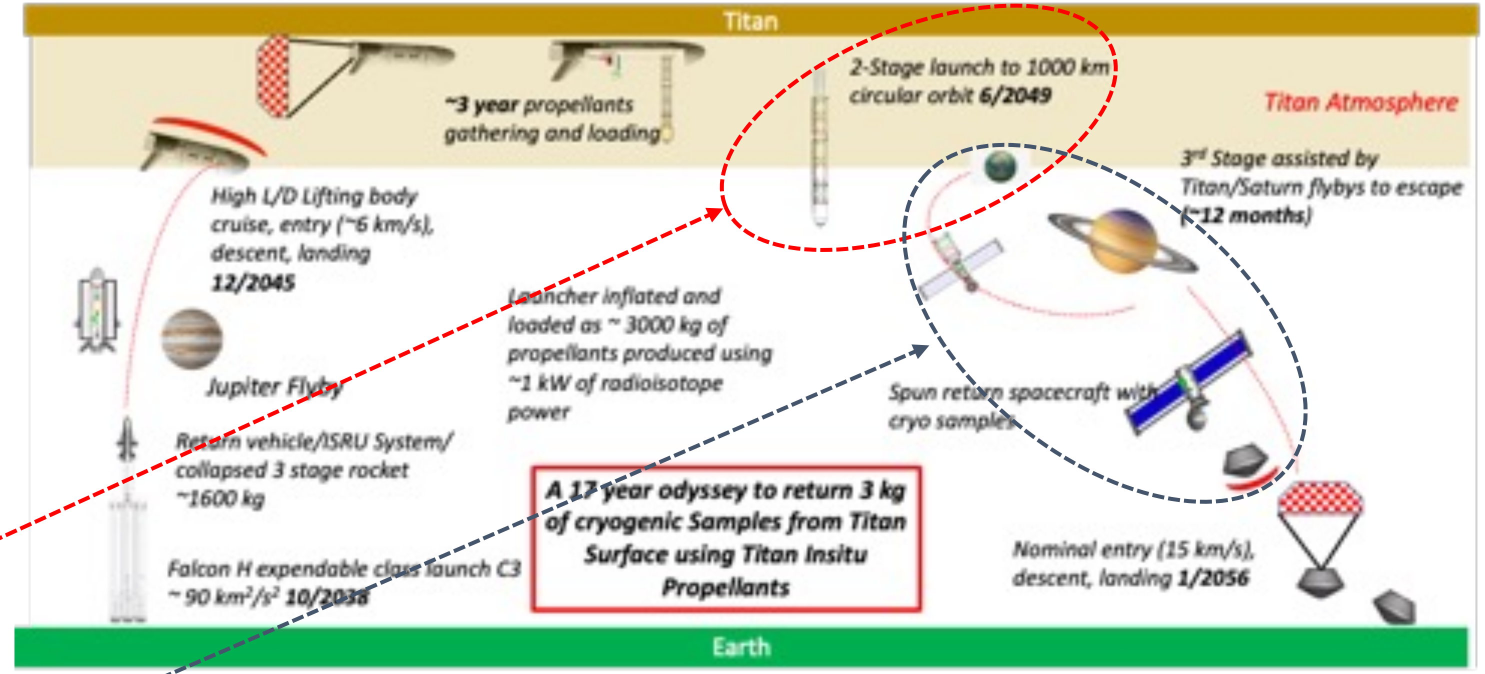
The work presented today was an analysis conducted as part of an engineering design proposed by NASA GRC's concurrent engineering design team, Compass. Under NIAC funding, the team proposed a Titan sample return mission that used in-situ fuel derived from Titan's environment to make a sample return mission feasible

Similar studies that did not use in-situ propellants required nearly ~10 ton earth departure mass to return a 3 kg cryogenic sample form Titan. By using in-situ propellants, the Compass team design only requires ~3 ton earth departure mass[1]

The mission proposed by Compass is can be broken down into legs:

1. Earth departure and in-space transit to Titan (including Titan landing)
2. Surface-to-orbit launch of the Titan Launch Vehicle (TLV) after a surface stay and in-situ propellants are are produced and stored
3. Earth return leg from high altitude parking/staging/phasing orbit at Titan

- The analysis presented in this paper focuses on the surface-to-orbit TLV, it's ascent trajectory and the associated ΔV and propellant requirements
- Return leg presented is another paper during this session



Summary of the Mission Concept of Operations (CONOPS). Image taken from "Mission Incredible A Titan Sample Return Using In-Situ Propellant"[1]

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

Titan Launch Vehicle: Sample Return Mission, Background and Motivation

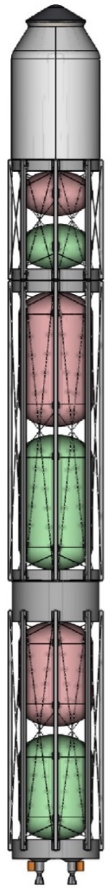
Titan presents a unique challenge to LV analysis. It has a very thick, dense atmosphere (density at the ground 4x that of Earths and extends 100's to ~1000km) but it has very low gravity (13% g_{earth})

Analysis objective: Design and simulate an ascent trajectory for a 3800 kg, wet mass and optimally maximize a delivered payload to a 1000 km, circular orbit under design and mission constraints set by the Compass team

- Resulting ΔV's, propellants and masses were reported to the Compass team for design considerations

➢ **Summary:** A feasible trajectory was found that optimized (within design constraints) a delivered mass of 1009 kg to a 1000 km, circular orbit for an initial, total mass of 3800 kg. The simulated vehicle consumed 2577 kg of propellant to provide a total ΔV of 3.96 km/s.

- The final, nominal trajectory was feasible, nicely converged and with masses and propellant consumption matching within reasonable tolerances of the Compass final design



CAD representation of the two-stage-to-orbit TLV designed by the Compass team

Titan Launch Vehicle: Titan LV Model Development

Numerical Tool: Trajectory will be optimized using software called Optimal Trajectory through by Simulation (OTIS v4.0)[3] with masses and GR&A provided by the Compass team

- OTIS is primarily a three-degree of freedom, point-mass optimizer with a user defined objective function (e.g. min/max mass, time of flight, ΔV, etc …) and user defined numerical constraints
- OTIS is a general simulation and optimization tool and interfaces to various, well-known optimizers. All results in this analysis were obtained using OTIS and its interface to the **Sparse Nonlinear OPTimizer (SNOPT)**

LV analysis requires: (bold faced items will be discussed in more detail)

Sub-system Model/Decison	Approach/Source
Preliminary vehicle design (masses, stages, etc …)	**Two-stage-to-obit (TSTO)**
Trajectory design	**Initial climb, pitch over, a burn-coast-burn trajectory**
Central body model	NIAF database
Atmosphere model	**Tabular lookup from reference**
Aerodynamic model	Mach dependent Cd for classic "missile shape" rocket, Cl = Cc = 0
Propulsion model(s)	**Altitude (Patm) dependent table lookup**

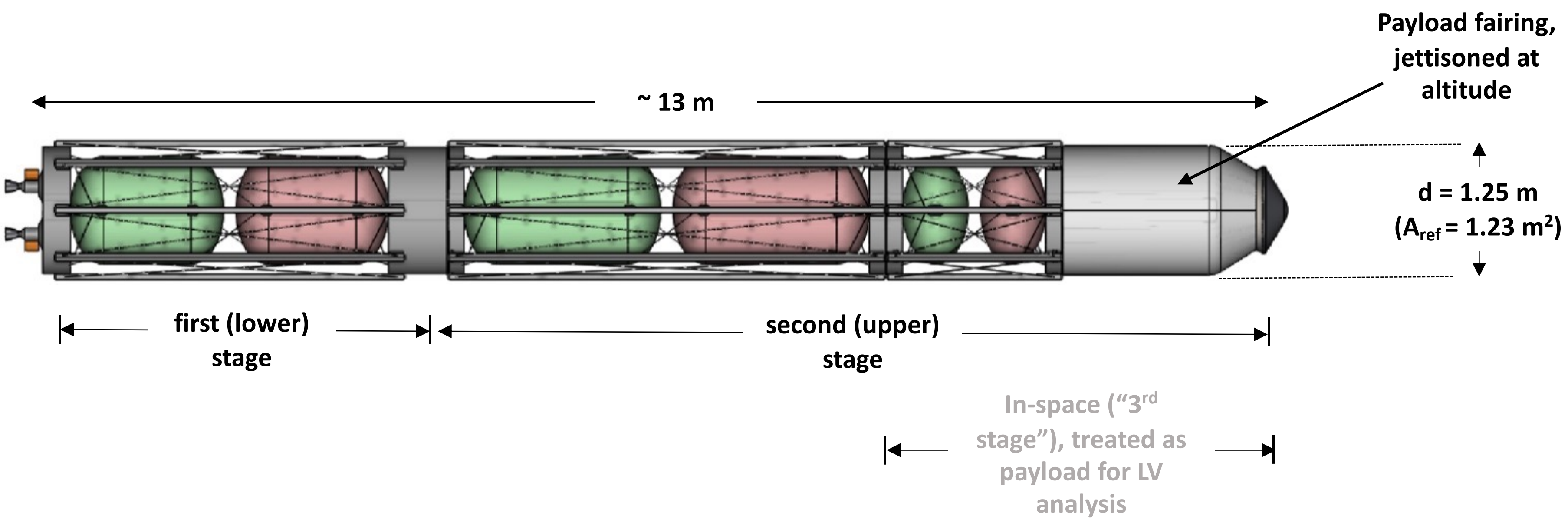
3. S.W. Paris, J.P. Riehl, W. Sjauw and R. Falck, Optimal Trajectories by Implicit Simulation: OTIS. Version OTIS 4, Vols. I to IV, Export Controlled International Traffic in Arms Regulations Document, 2008.

Titan Launch Vehicle: Approach (Vehicle Stages)

Two-Stage to Orbit:

Early in the design cycle, it was decided that the LV would take the advantage of staging. Specifically, the Titan LV was designed with two stages

- Classic approach to address "mass penalty"
- Offers the ability to configure propulsion for different atmospheric regimes



CAD representation of the two-stage, TLV with fist and second stages noted. The second stage is designed to separate once inserted and an in-space stage then carries the Titan sample back to Earth. The LV problem ends at orbit insertion at to the LV problem, the rocket is two-stages with the earth return stage being part of the payload system

Titan Launch Vehicle: Approach (Trajectory Design)

Burn-Coast-Burn Trajectory:

The design trajectory is depicted schematically in the figure to the right

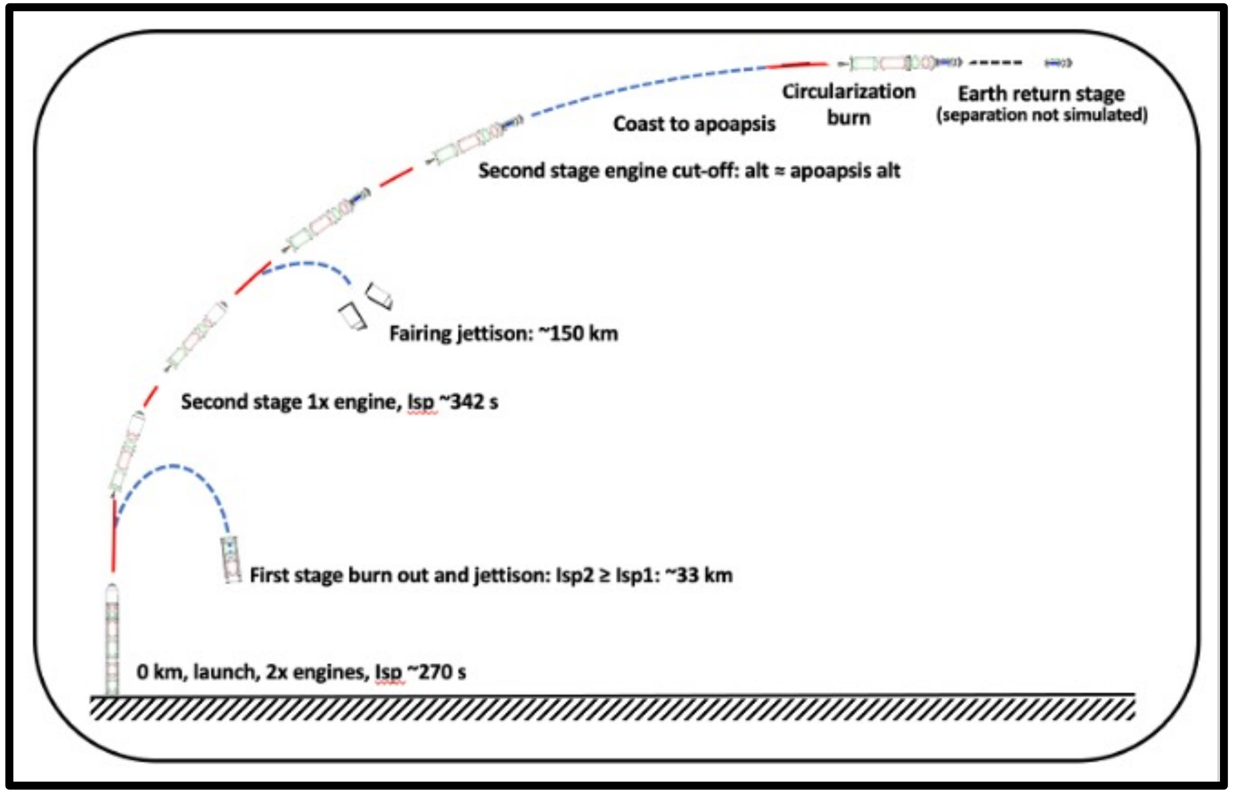
Fairly straight/simple approach designed to take advantage of low gravity by preforming a burn-coast-burn strategy to save propellant by shutting off the engines due to the low gravity on Titan

Burn-coast-burn trajectory approach is common approach on other celestial bodies, but typically not when they have thick atmospheres (e.g. Mars Ascent Vehicle)[4]

- This approach is also believed to be like similar sample return mission, against which results from this study were compared[5]

Trajectory design features

- Optimizer is permitted to pick a path through the lower atmosphere to a pitch-over point that best balances gravity loss terms with drag loss terms to minimize overall propellant usage (maximize delivered mass)
- Staging point is also optimally determined and primarily driven by the staging advantage and favorable propulsion
- The active controls for steering are time varying, optimal (above a hold altitude) and are in-plane, pitch-only



4. 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.
5. B. Donahue, "Titan Sample Return Mission Concept.", 57th JANNAF Propulsion Meeting, Colorado Springs, CO, 2010

Titan Launch Vehicle: Atmosphere Data and Implementation into the OTIS Model

Atmosphere Model:

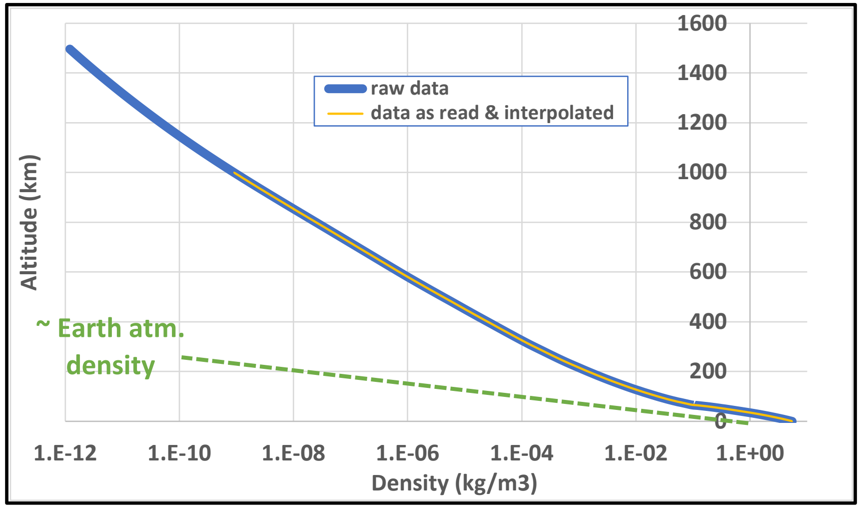
Titan GRAM was not integrated into OTIS, so data was obtained from the provided reference and incorporated into OTIS through tabular lookups[6]

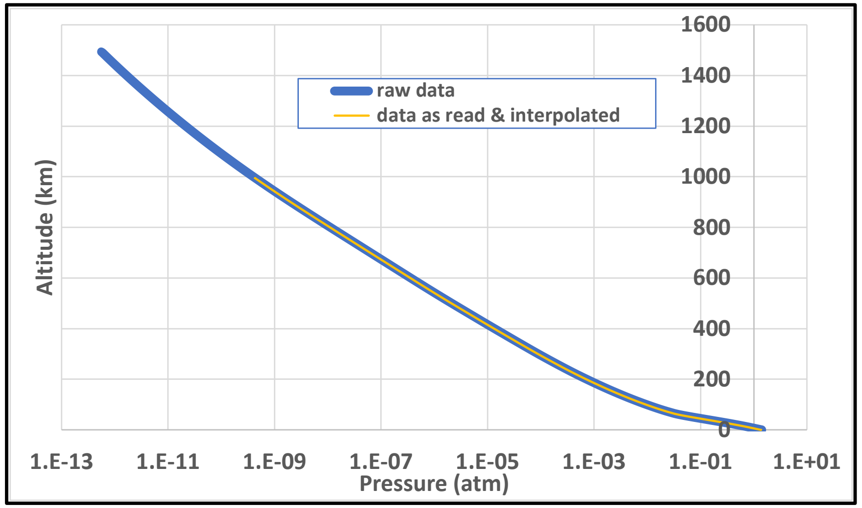
- The raw data for density, pressure and temperature are plotted with the solid blue plot indicates raw data and the representation in OTIS overplotted in yellow

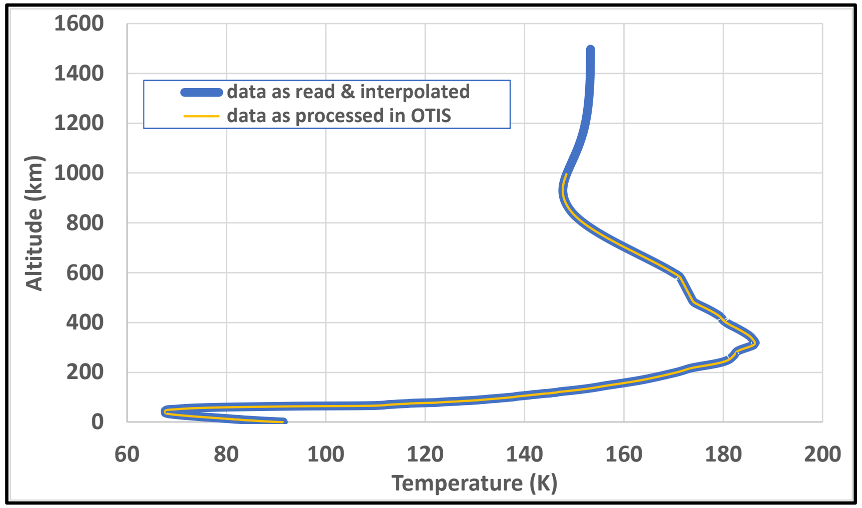
  A schematic representation of Earth's density is included (dotted green line) as a reference

  ➢ Titan's atmosphere is dense & thick

- Drag model requires Mach dependent Cd table lookup, SoS calculated using standard SoS equation with parameters valid for Titan
- This implementation did not include the effect of winds







6. 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.

Titan Launch Vehicle: Propulsion Model

Propulsion Models:

Data tables provided by Compass Propulsion Sub-System Team

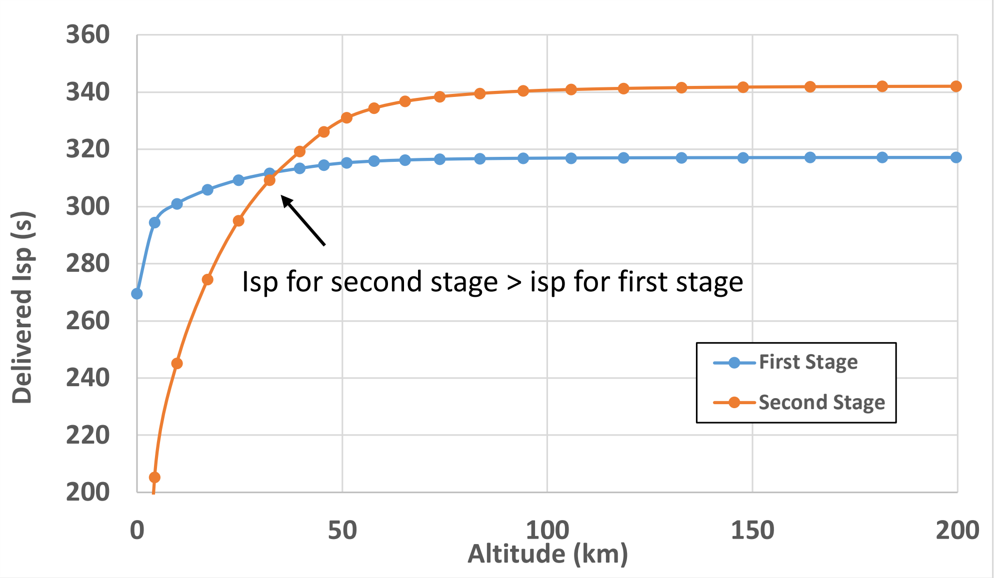
First and second stage propulsion are L02/LCH4 (pumped)

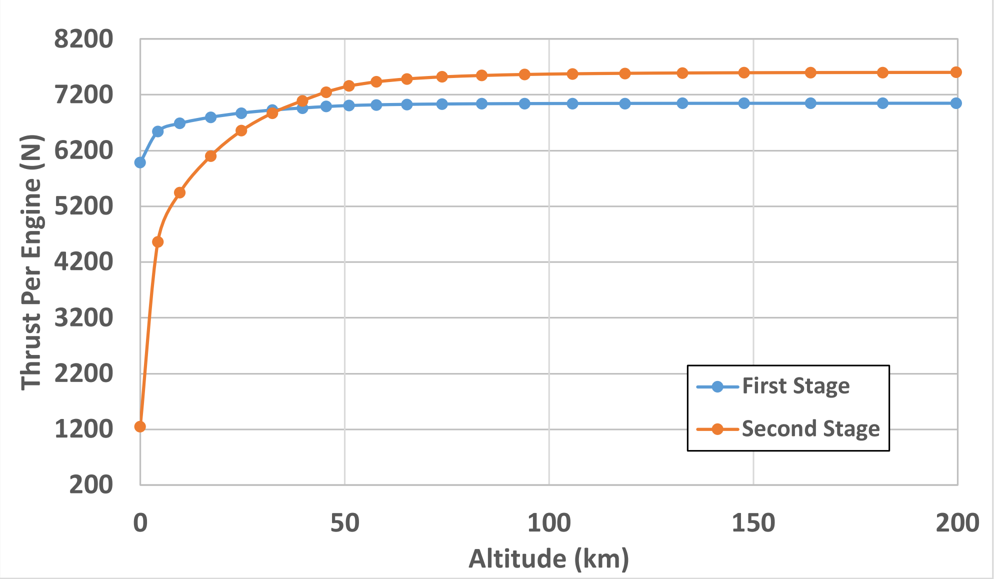
The first stage is equipped with 2 engines, each capable of delivering 6200 N of thrust (Isp = 270) while the second stage only has 1 engine tuned to perform with higher I_{sp} (at altitude) with vacuum I_{sp}=342 s

Both stages are equipped with an optimal, time-dependent throttle allowed to vary the thrust between 25% to 100%

First stage burnout (and jettison) altitude is optimally determined and driven by favorable propulsion (I_{sp}) balanced against first stage mass jettison

- The stage mass was computed as a 17% mass fraction of propellant consumed





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Titan Launch Vehicle: Nominal Trajectory Results

Resulting mass, ΔV and OTIS propellant summary used by the Compass team for design consideration

Results provided in table split by stages and flight phases

- Initial, gross lift-off mass (GLOM) of 3800 kg results in a final burn out (BO) mass of 1009 kg at 1000 km, circular
  - These masses match to the final Compass design to within reasonable tolerances and closes the entire LV to return legs of the mission
- Total ΔV = 3.964 km/s for a 72 min ascent and consumes 2577 kg of propellant
- The initial burn requires ΔV = 3.766 km/s while the circularization burn only requires a ΔV = 198 m/s
- First stage depleted (and jettison) at ~33 km with a burn out mass = 193 kg
- Simulation includes dropping a faring at an altitude of 150 km ("above the atmosphere")

➢ First stage carries roughly 25% of the total ΔV and a little less than half (~45%) of the total propellant

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)

Titan Launch Vehicle: Trajectory (Altitude & Velocity)

Altitude and Velocity:

The initial climb (apoapsis burn) is accomplished by the first and second stages with the first stage jettison occurring at an altitude of 32.9 km

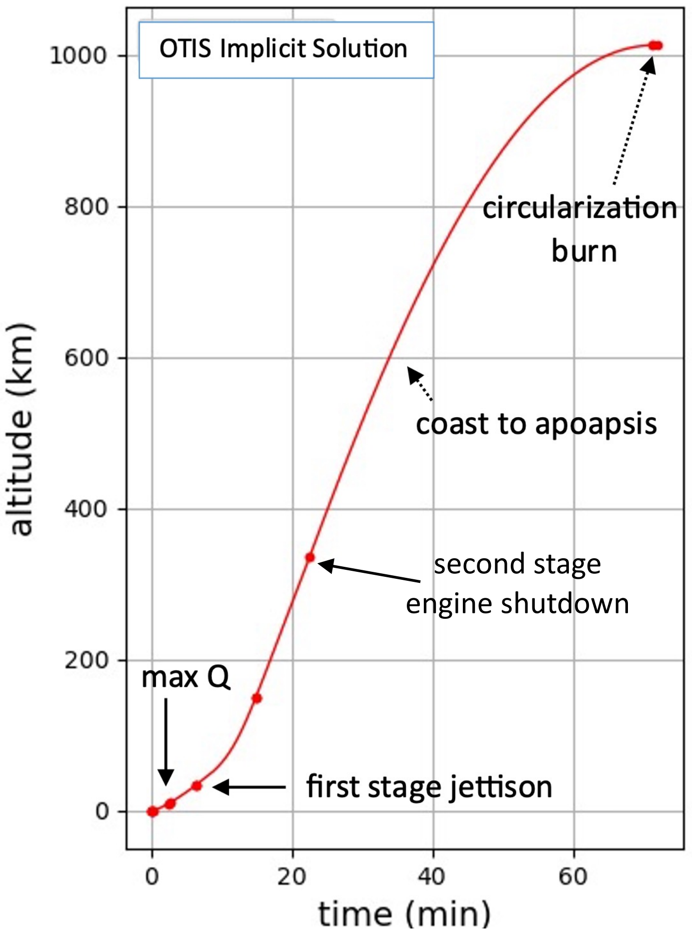
- Velocity is only ~100 m/s at the first stage jettison, near the end of the initial vertical rise (~40 km)

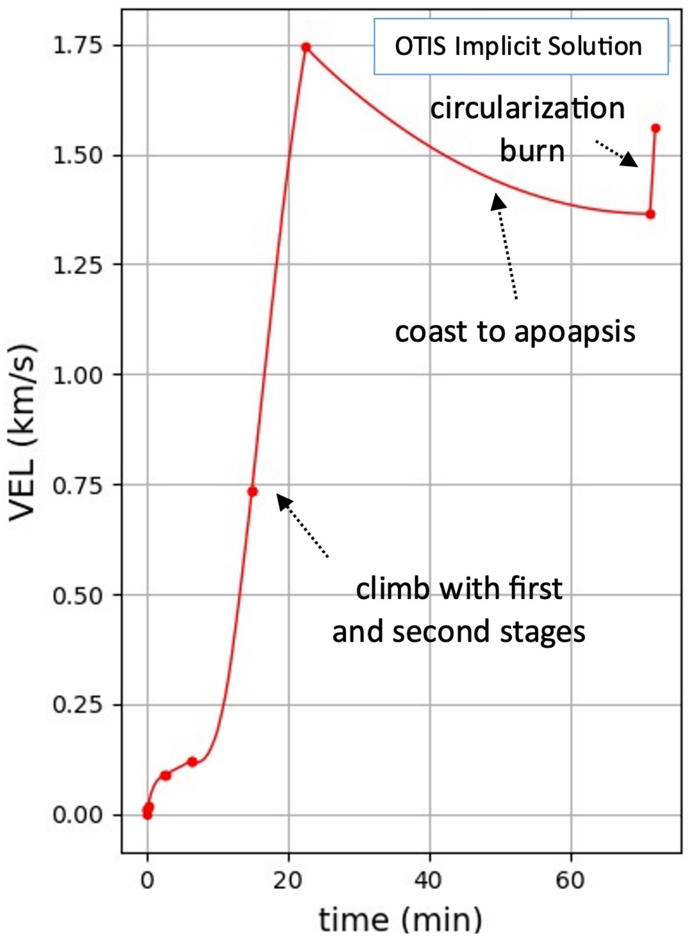
The duration of the first burn (both stages) lasts for approximately 23 min and ends at an altitude of near 335 km (HA ≈ 1000 km)

The velocity at the end of the first burn > 1.75 km/s (> circ velocity @ 1000 km)

The LV loses velocity during the coast to apoapsis where it then inserts into orbit with a brief circularization burn

The circularization burn is short (< 1 min)





Time dependent trace of altitude and velocity, red points represent OTIS phase boundaries and are provided as points of reference

Titan Launch Vehicle: Trajectory (Flight Path Angle)

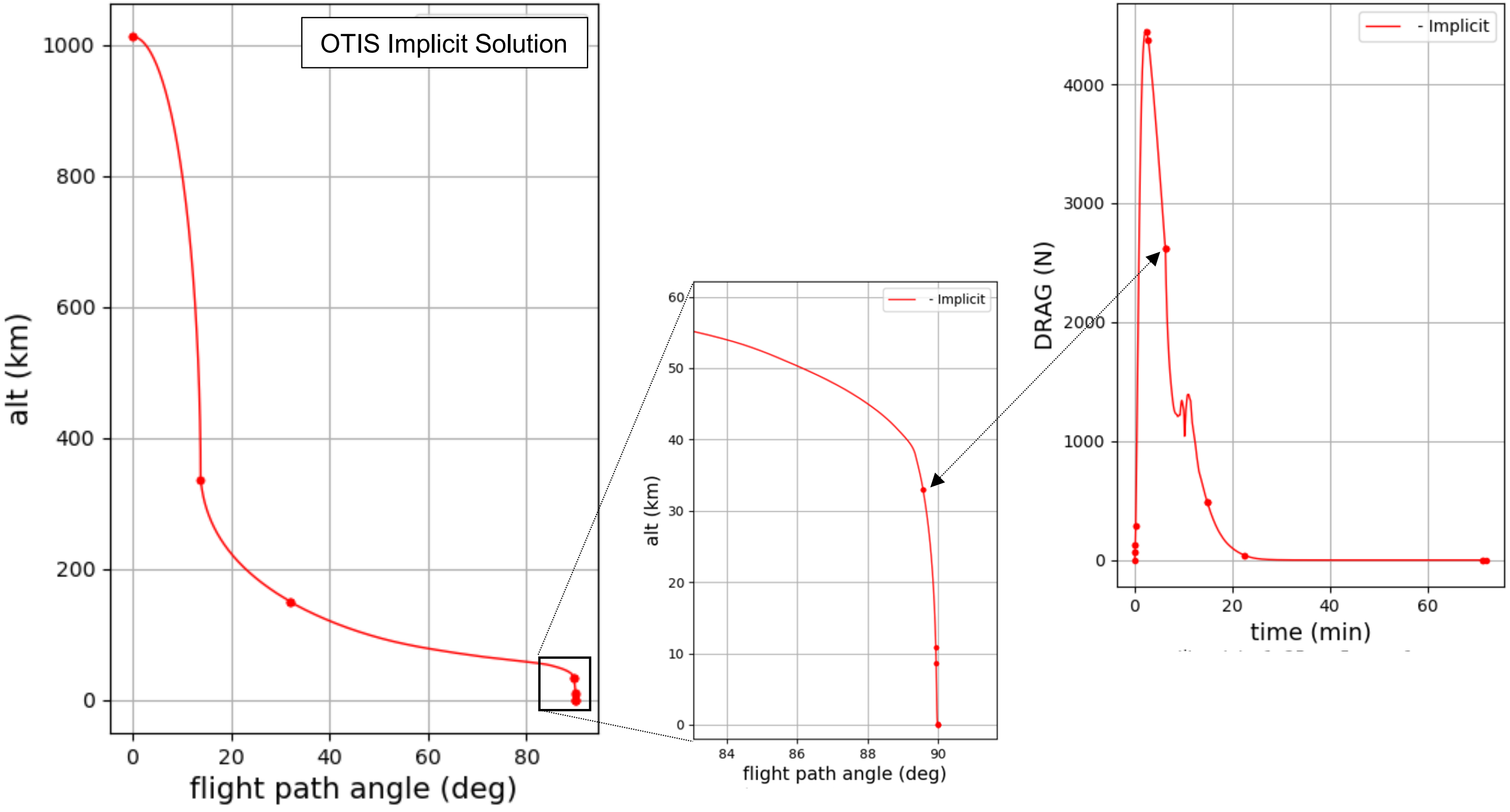
Flight Path Angle:

The plot of flight path angle as a function of altitude (with an insert focusing on the lower portion of the ascent) illustrates the altitude of the initial climb through the lower atmosphere

OTIS is free to pitch over much lower but selects an altitude of approximately 40 km ± as the optimal altitude to begin pitch over and begin building its downrange velocity

This pitch-over altitude results from the optimizer balancing gravity losses which are maximum while climbing vertically against high drag losses in the lower atmosphere

As a point of reference, pitch-over point in the drag profile is indicated



Altitude plot of flight path angle and time dependent plot of drag force. Red points represent OTIS phase boundaries and are provided as points of reference

Titan Launch Vehicle: Trajectory (Q and T/W)

Dynamic Pressure:

The time history of dynamic pressure (Q) illustrates that the Q at Q_{max} is on the order of 14k N/m^2

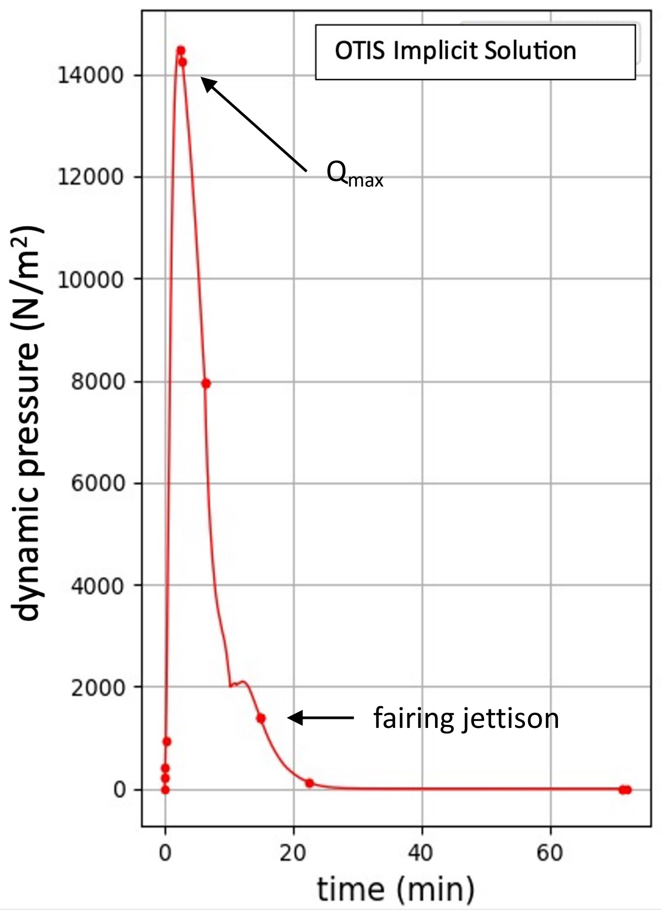
- Q_{max} occurs ~10 km while the LV is still vertical

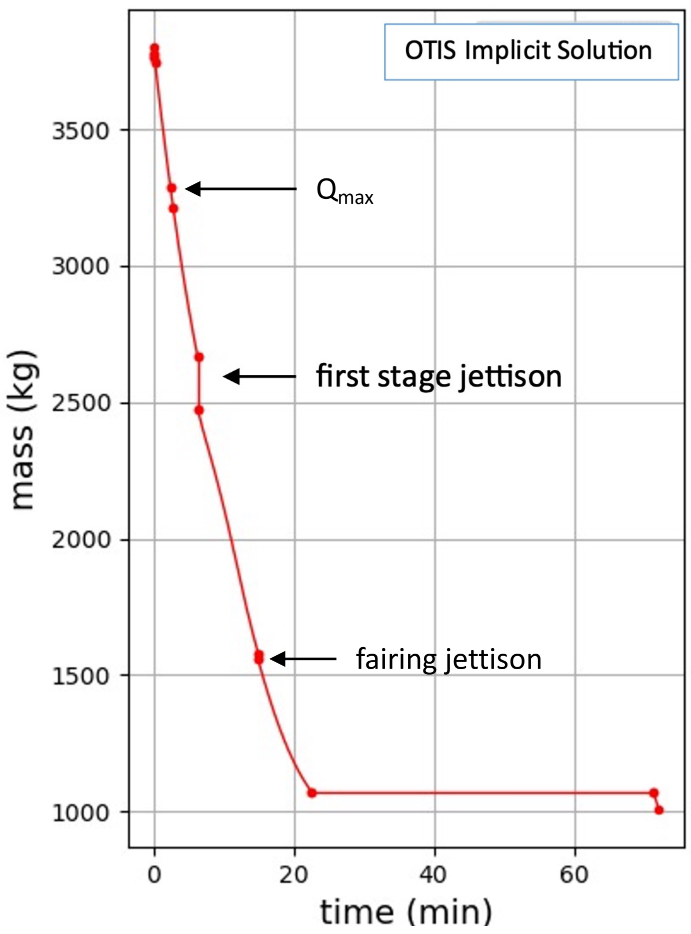
Mass:

A plot of illustrates the time history of the LV with the initial mass of 3800 kg resulting in ~1009 kg at insertion

Most of the overall mass consumption is propellant with the first stage jettison (193 kg) payload fairing jettison (22 kg) accounting for the rest

The payload faring jettison occurs sufficiently hither than Q_{max} where Q < 2000 N/m^2. This was considered a safe condition for the jettison





Plots of dynamic pressure (Q) and T/W. Red points represent OTIS phase boundaries and are provided as points of reference

Titan Launch Vehicle: Trajectory (Thrust & Mass)

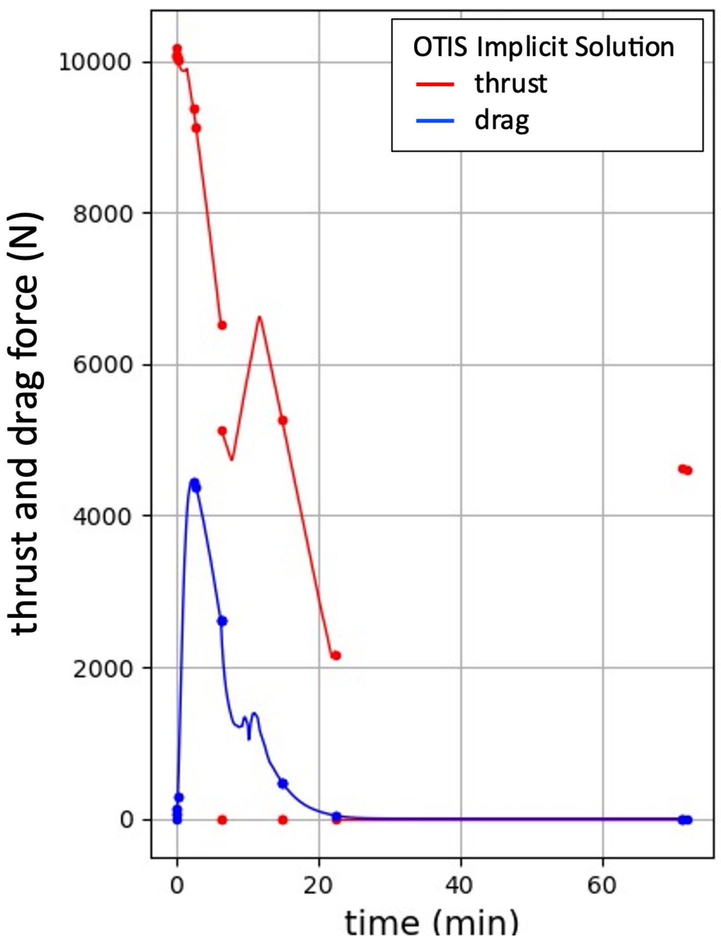
Thrust, Drag, and T/W

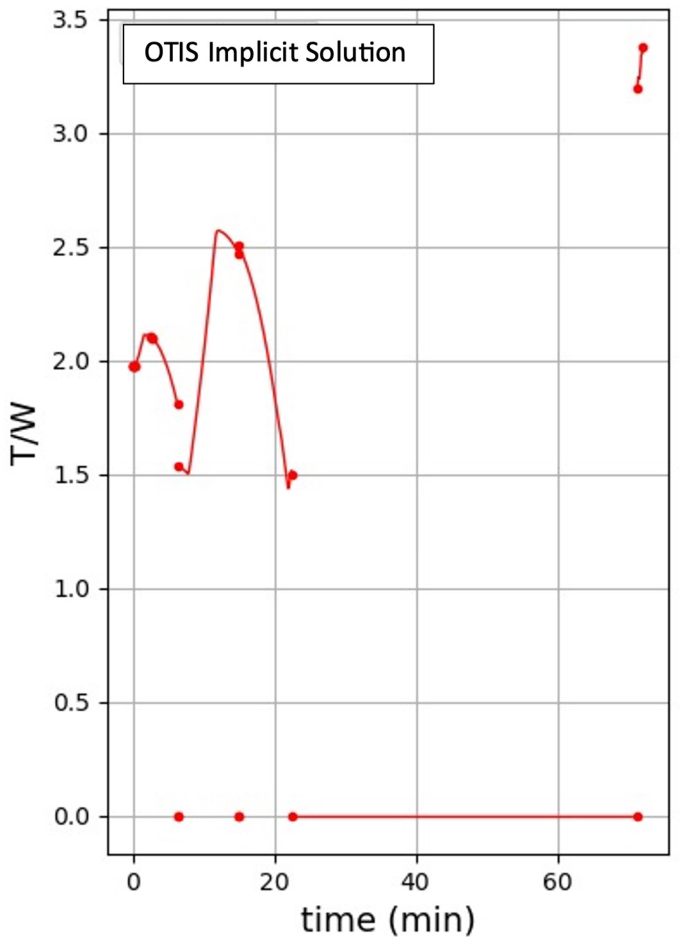
Thrust and drag are plotted on the same scale and illustrate the relatively high thrust (>10k N) required by the first stage to achieve an initial T/W≈2

This initial thrust requires combined thrust of the 2-engines on the first stage (individual engine only capable of producing ~6.7k N)

The thrust is throttled as the LV depletes mass maintaining an approximate T/W ≈ 2 as the optimizer reduces velocity to minimize drag loss (at the expense of lower gravity loss)

The T/W profile indicates a gentle ascent with values ranging between 1.5 to 2.5 for the initial ascent and only approaching 3.5 during the final circularization burn





Time dependent trace of thrust, drag force and mass, red points represent OTIS phase boundaries and are provided as points of reference

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Titan Launch Vehicle: ΔV Sensitivity to Drag

The relationship between drag area and the resulting ΔV is shown on the right for an analysis performed with an early vehicle/trajectory design (not the nominal trajectory presented in the previous section)

The analysis was straight forward: trajectory was reconverged for varying drag reference areas

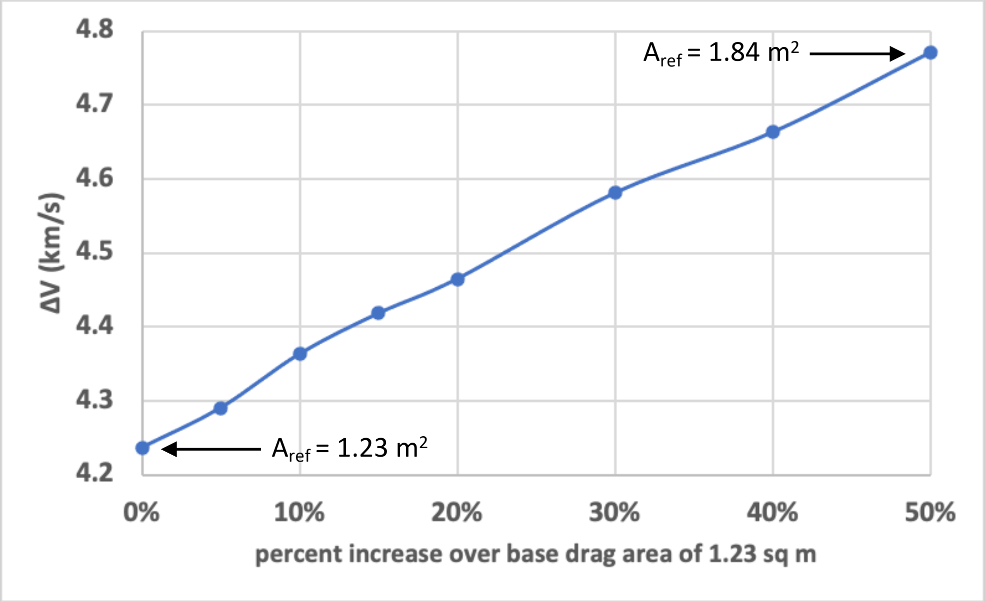
Resulting ΔVs are plotted against a % increase in reference area with the base $A_{ref} = 1.23\ m^2$ (based on a d = 1.25 m)

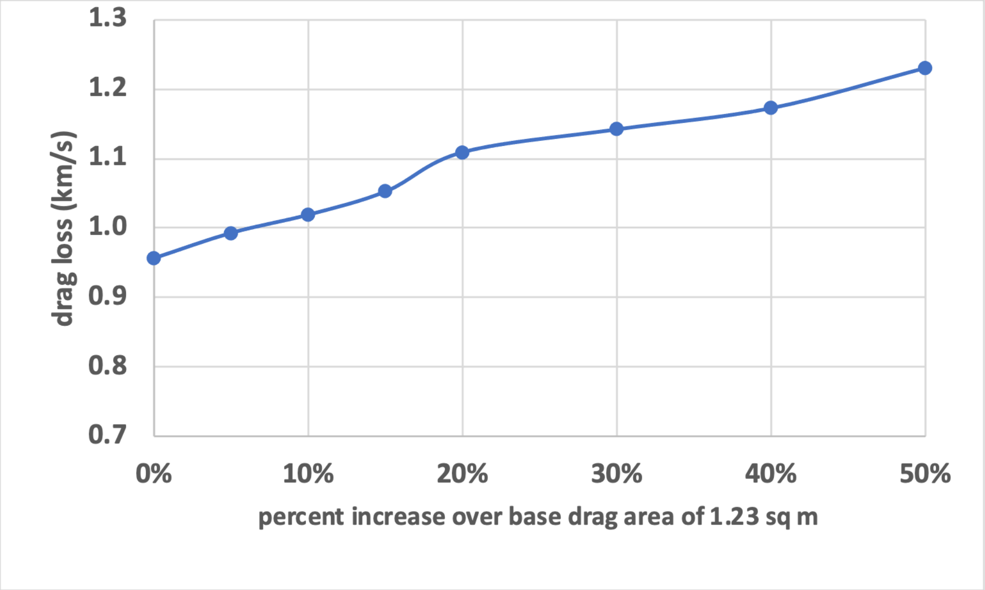
For reference: a 50% increase in A_{ref} corresponds to $A_{ref}' = 1.84\ m^2$ (d' = 1.53 m)

The trend in ΔV is nearly linear over the 0 to 50% range examined

- The trend is that for every 1% increase drag area, the ΔV increases by 12 m/s
- The end point (50% increase) adds nearly 600 m/s to the overall ΔV

Increasing drag area directly impacts the overall ΔV (as seen in the plot of the drag loss term), but the impact is compounded by an overall less efficient ascent leading to more losses overall





Titan Launch Vehicle: High Altitude Launch

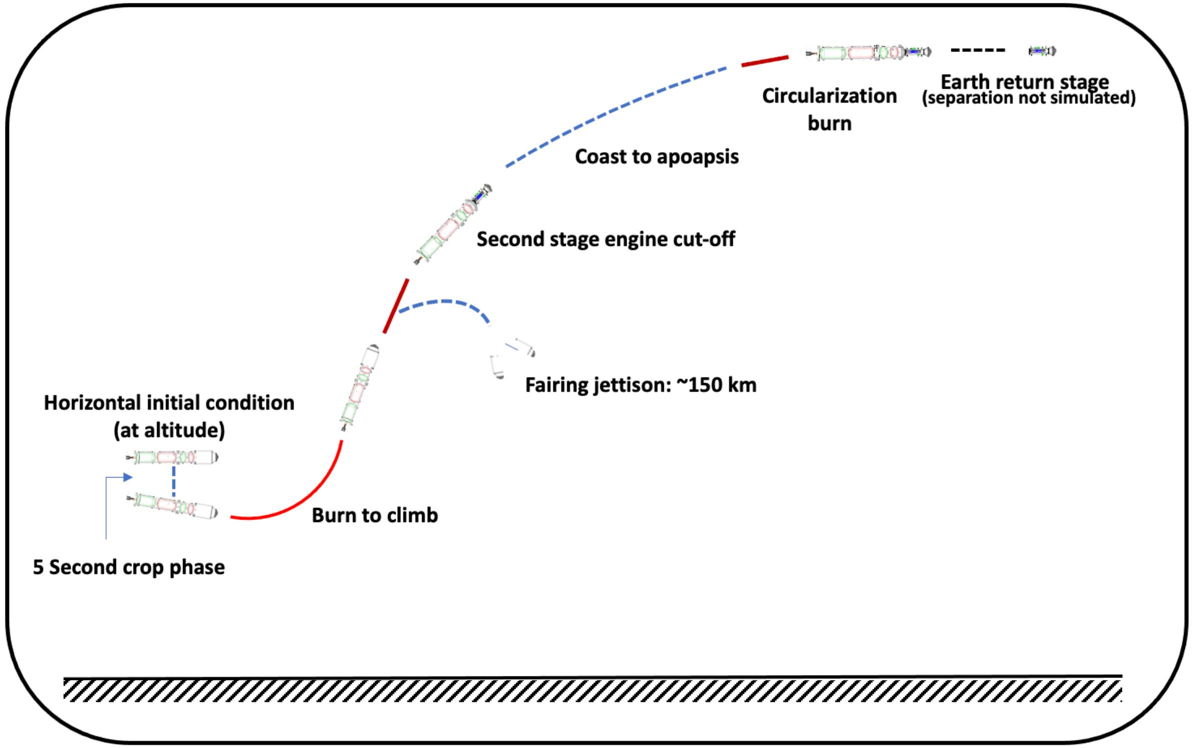
Preliminary analysis for a SSTO, "air launch" to determine potential ΔV savings for replacing first stage with something other than a rocket

The analysis does not consider the platform used to achieve the initial launch altitude: conceptually, it would be something like a balloon or a winged (fixed or rotary) vehicle

The analysis is repeated for various launch altitudes ranging from 45 km to 100 km and the results are compared

Trajectory Design

- The trajectory begins with the second stage from the nominal trajectory "suspended" horizontally at altitude
  - Initial mass fixed at 1500 kg
  - Objective: maximum delivered payload
- The vehicle is then dropped and falls (turning slightly nose down) for a fixed duration of 5 seconds
  - This drop phase is designed to allow the rocket to separate from its launch platform and generally provided 20 m of separation before ignition
- A series of flight phases are designed to simulate a powered climb to HA=1000 km and alt > 200-300 km, where the engine is permitted to shut down
- The remainder of the phases followed the surface launch strategy and included: unpowered coast and a circularization burn



Titan Launch Vehicle: High Altitude Launch (Results)

The following tables summarize the ΔV findings and final mass to orbit for a sweep of launches from an altitude of 45 km to 100 km (initial mass at drop = 1500 kg, fixed)

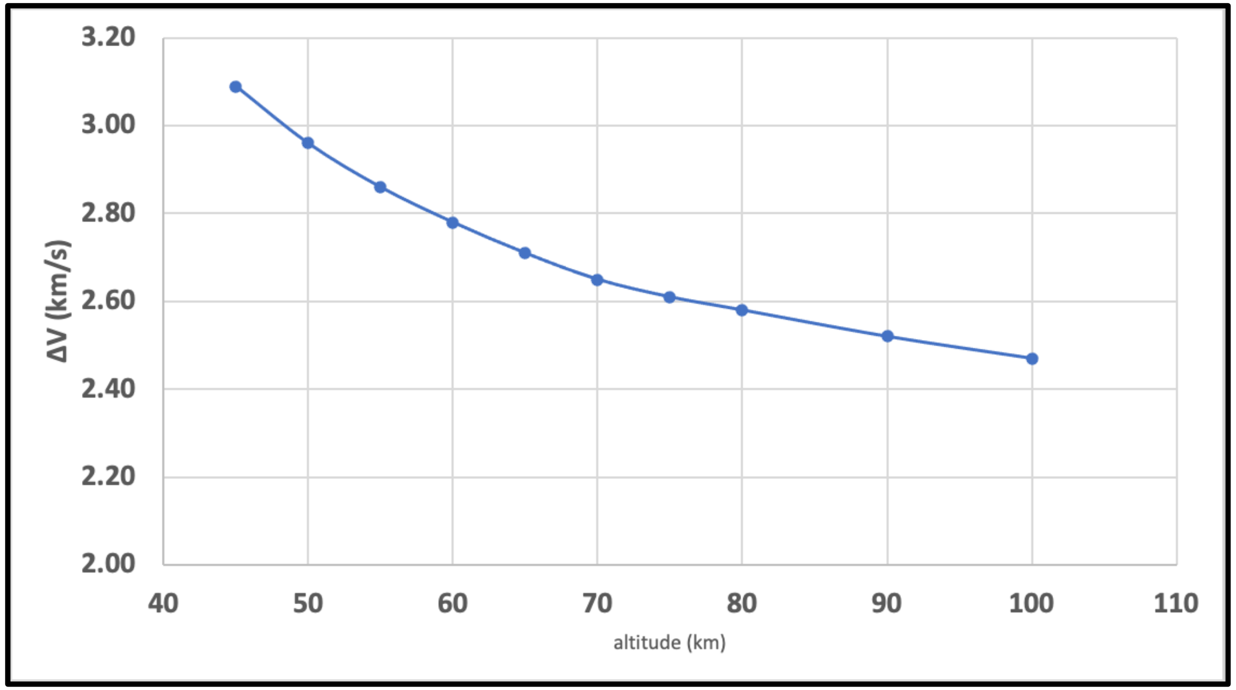
The ΔV savings for launching at altitude are predictable and obvious with a lower overall requirement on ΔV with a ~1 km/s over the nominal trajectory for the surface launch at 50 km

It should be noted that this analysis was preformed early in the study and did not result in the same delivered payload as compared to the base case

The results are intriguing and suggest potentially significant savings for launching at altitude, but the analysis should be redone with a fixed delivered mass and an objective to minimize initial mass

Any potential savings for launching at altitude would need to be balanced against the cost and complexity of designing an alternative first stage

- One additional consideration and potential advantage of the air launch may be the size of the total system
- High altitude launch may be able to reduce ΔV requirements and would result in a smaller LV stack



Titan Launch Vehicle: Summary

The resulting, nominal trajectory is generalized as starting with a long, vertical, slow climb as the optimizer chooses a path through the atmosphere to balance drag losses against accumulated gravity losses. Following the initial, vertical climb, the vehicle pitches over, jettisons the first stage and continues its ascent adding velocity with the second stage. The second stage then shuts off to save propellant, coasting to apoapsis where it reignites to circularize.

The total ascent takes 72 minutes (48 minutes of coasting), consumes 2577 kg of propellant and requires a ΔV of 3.9 km/s

The optimizer chooses a flight path within the constraints of the problem that appears to minimize drag losses in the lower portion of the atmosphere against gravity losses accumulated through the ascent. Drag losses account for nearly 25% (~1 km/s) of the total ΔV

The resulting trajectory was well converged, feasible with all constraints met and masses and propellant requirements matching to within a reasonable tolerance with the final Compass Team design

A comparison to a previous study indicates a ΔV = 3.9 km/s was higher than the 3.3 km/s the reported[5]

- However; the previous study may not be including a circularization burn in their results so the comparison may not be direct
- Comparing the results with the circularization burn taken into consideration results in a match on the order of 10-12% which could be accounted for in modeling/trajectory assumptions with most likely difference being the treatment of the atmosphere and drag models

An analysis of ΔV sensitivity to drag area indicates that the resulting ΔV is highly sensitive to drag (which is to be expected) and emphasizes the importance of designing aerodynamically efficient vehicles if they are to launch from the surface of Titan

A preliminary investigation of launching at altitude suggests potentially significant ΔV savings

- Approach suggests that using Titan's thick, dense atmosphere to the mission's advantage, but benefits must be balanced against the added complexity (and cost) of designing a platform capable of high-altitude launches

5. B. Donahue, "Titan Sample Return Mission Concept.", 57th JANNAF Propulsion Meeting, Colorado Springs, CO, 2010

Titan Launch Vehicle: 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] Lorenz, R. *Saturn's Moon Titan: Owners' Workshop Manual, Haynes, 2020*

[4] S.W. Paris, J.P. Riehl, W. Sjauw 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.

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[6] *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.*

Backup Charts

Titan Launch Vehicle: Background on Titan

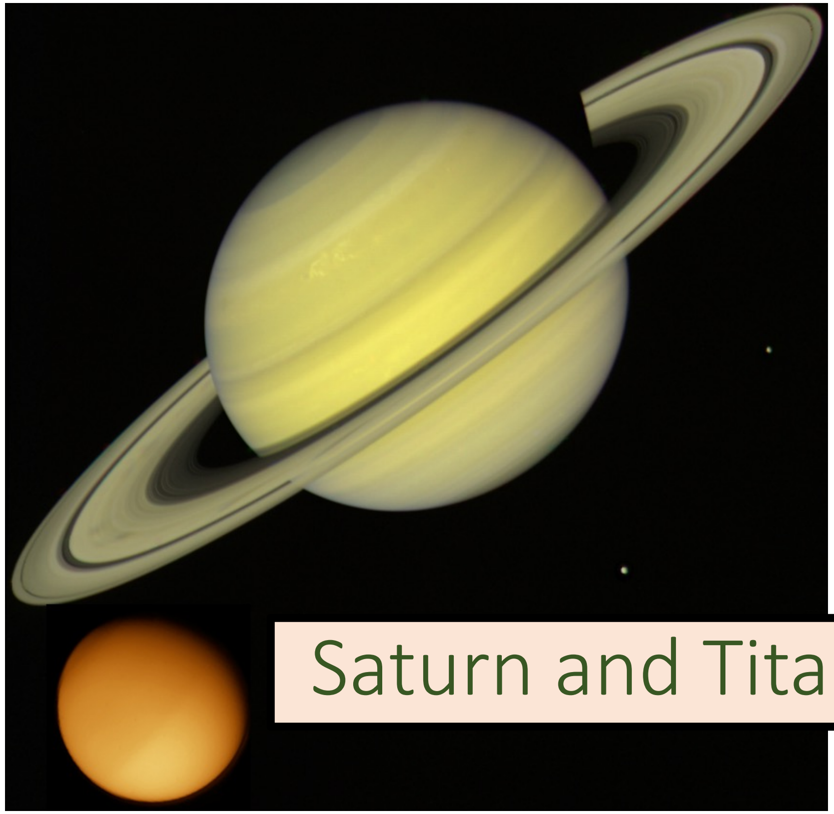
Why Titan? Titan is a moon of Saturn and is a celestial body of significant scientific interest [2]

- Only moon in the solar system with dense atmosphere
- Organic rich environment with evidence of liquid hydrocarbon oceans
- Titan is the target of the next NASA New Frontiers mission, Dragonfly, which will fly in the Titan atmosphere to access multiple sites on the surface
- Is a priority for astrobiology due to the existence of complex organic molecules

Due to its distance from Earth, Titan missions are energetically challenging and sample return missions are extremely complicated, long in duration and expensive in terms of propellant and mass

A key component of the proposed mission from the Compass team, in-situ propellants are used to reduce the earth departure mass requirements

- The ability to launching from the surface with a sample return vehicle a key component of the proposed mission and it is the focus of this study



Saturn and Titan

Launching from Titan is a unique and challenging LV problem with an interesting ascent profile

- Titan's atmosphere is more that 4x as dense as Earth's at the surface while its gravity is approximately 13% that of Earth's
- The weak gravity pull on Titan allows its atmosphere to extend to very high altitudes (~multiple 100's to 1000 km). For this study, we assumed 1000 km was a suitable altitude for orbit stability due to drag
- The interplay between high drag losses in Titan's atmosphere and low gravity losses, gives rise to a unique ascent trajectory

2. Lorenz, R. *Saturn's Moon Titan: Owners' Workshop Manual, Haynes, 2020*

Titan Launch Vehicle: OTIS Phasing Schematic and Key GR&A Summary

forward time

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

The OTIS phasing "flow chart" schematic on the left summarizes the numerical problem organization

Ending conditions and key constraints are defined

Key points from the chart include:

- The steering is implemented as in-plane, pitch only ascent
- Altitude for 1st stage jettison constrained between 30 and 35 km (could be relaxed)
  - This keeps the solution "stable" and results with two stages of similar size

Titan Launch Vehicle: Central Body and Aerodynamic Model

Central Body and Gravitational Model Implementation

The ascent flight was modeled as a two-body problem with Titan as the central body and the LV as the secondary

- Central body parameters for Titan (radius, flattening, etc …) and gravitational parameters were implemented via OTIS's embedded interface to the Navigation and Ancillary Information Facility (NAIF) celestial body data base
- A zonal gravity model was implemented with J though J_4 terms included
- Gravitational perturbations from third bodies (e.g., Saturn) were not included for the level of fidelity considered during this study

Aerodynamic Model

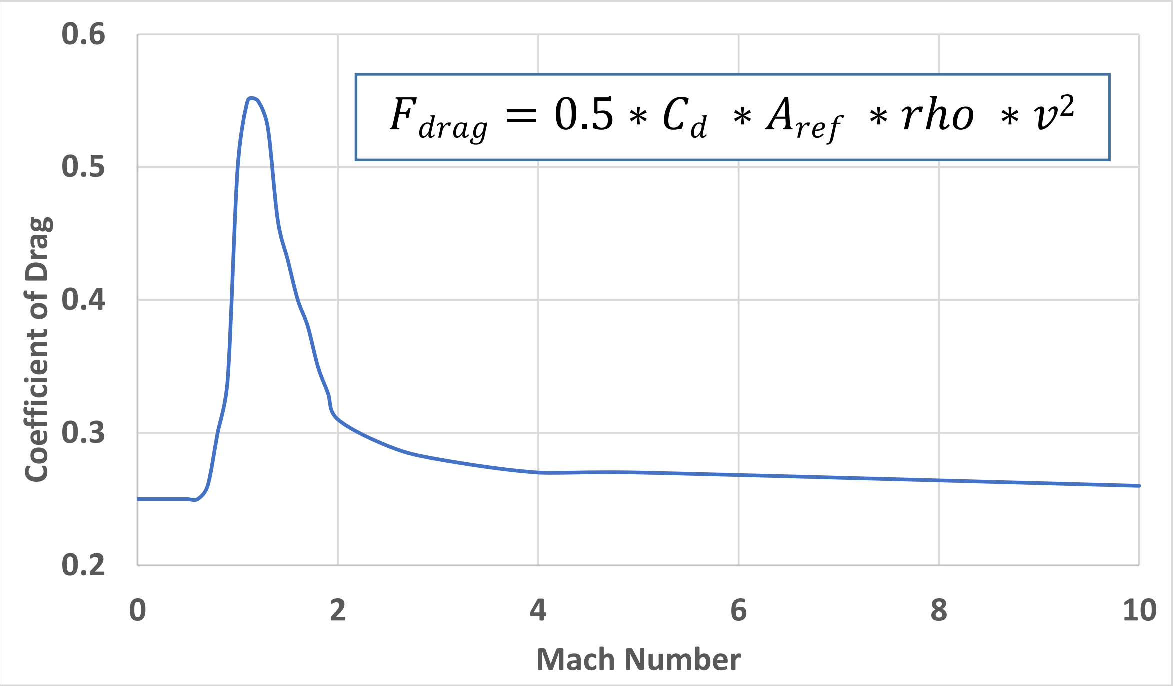
OTIS's standard drag model was used with a drag coefficient (Cd) obtained as a function of Mach

Titan LV represented as a simple "missile" shape with C_d data were obtained from the Propulsion sub-system team lead for inclusion in OTIS and depicted in the plot on the right

Aerodynamic lift (Cl) and cross-component drags (Cc) were not considered in this study (i.e. Cl = Cc = 0)

The reference drag area for all simulations presented in this paper (except when otherwise noted) was:

A_{ref} = 1.23 m^2 (reference design diameter = *1.25 m*)



Series of slides to animate results table. All information is the same as on the static chart with highlights

Titan Launch Vehicle: Nominal Trajectory Results

Resulting mass, ΔV and OTIS propellant summary used by the Compass team for design consideration

Results provided in table split by stages and flight phases

- Initial, gross lift-off mass (GLOM) of 3800 kg results in a final burn out (BO) mass of 1009 kg at 1000 km, circular
  - These masses match to the final Compass design to within reasonable tolerances and closes the entire LV to return legs of the mission
- Total ΔV = 3.964 km/s for a 72 min ascent and consumes 2577 kg of propellant
- The initial burn requires ΔV = 3.766 km/s while the circularization burn only requires a ΔV = 198 m/s
- First stage depleted (and jettison) at ~33 km with a burn out mass = 193 kg
- Simulation includes dropping a faring at an altitude of 150 km ("above the atmosphere")
- ➢ First stage carries roughly 25% of the total ΔV and a little less than half (~45%) of the total propellant

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)

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Series of slides to animate altitude & velocity plots. All information is the same as on the static chart with highlights

Titan Launch Vehicle: Trajectory (Altitude & Velocity)

Altitude and Velocity:

The initial climb (apoapsis burn) is accomplished by the first and second stages with the first stage jettison occurring at an altitude of 32.9 km

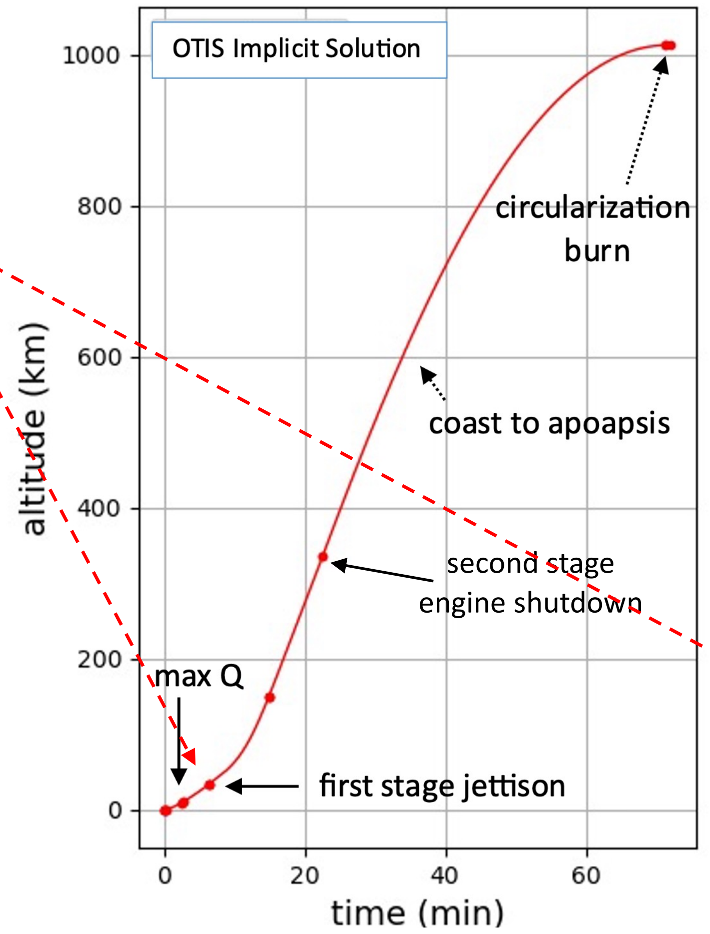
- Velocity is only ~100 m/s at the first stage jettison, near the end of the initial vertical rise (~40 km)

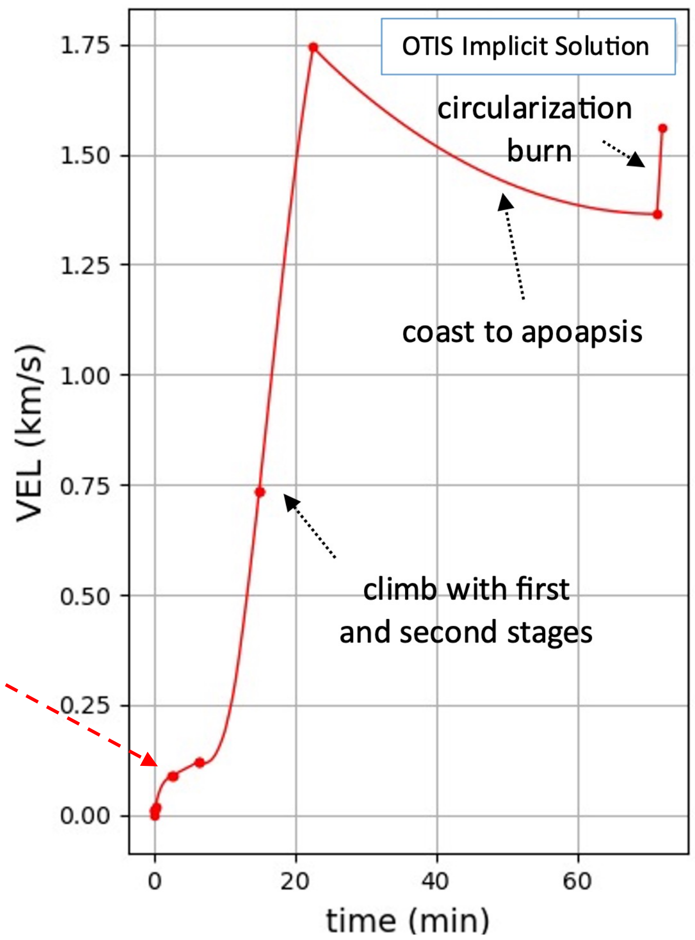
The duration of the first burn (both stages) lasts for approximately 23 min and ends at an altitude of near 335 km (HA ≈ 1000 km)

The velocity at the end of the first burn > 1.75 km/s (> circ velocity @ 1000 km)

The LV loses velocity during the coast to apoapsis where it then inserts into orbit with a brief circularization burn

The circularization burn is short (< 1 min)





Time dependent trace of altitude and velocity, red points represent OTIS phase boundaries and are provided as points of reference

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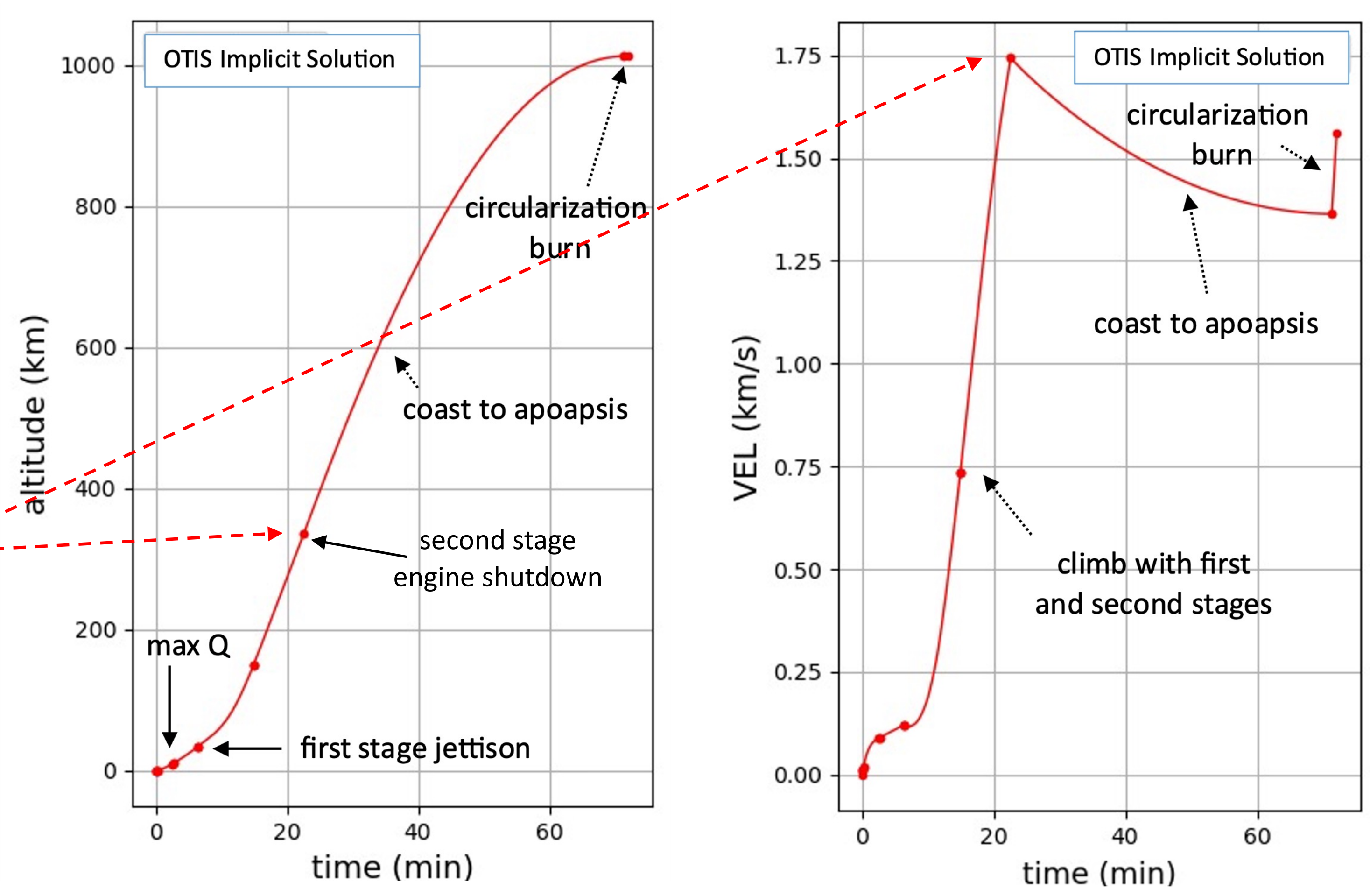

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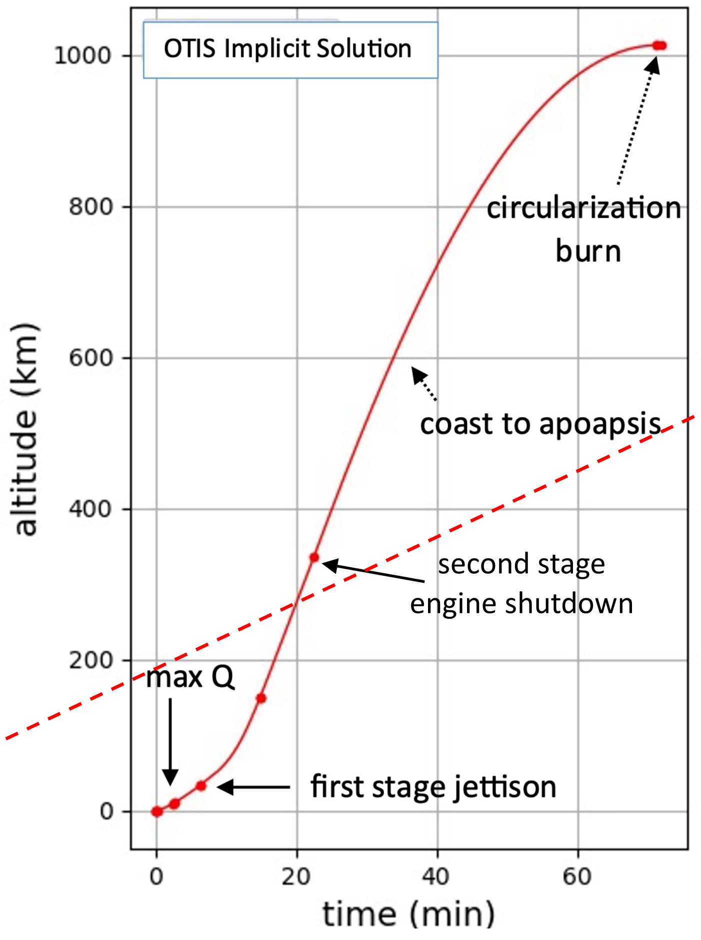

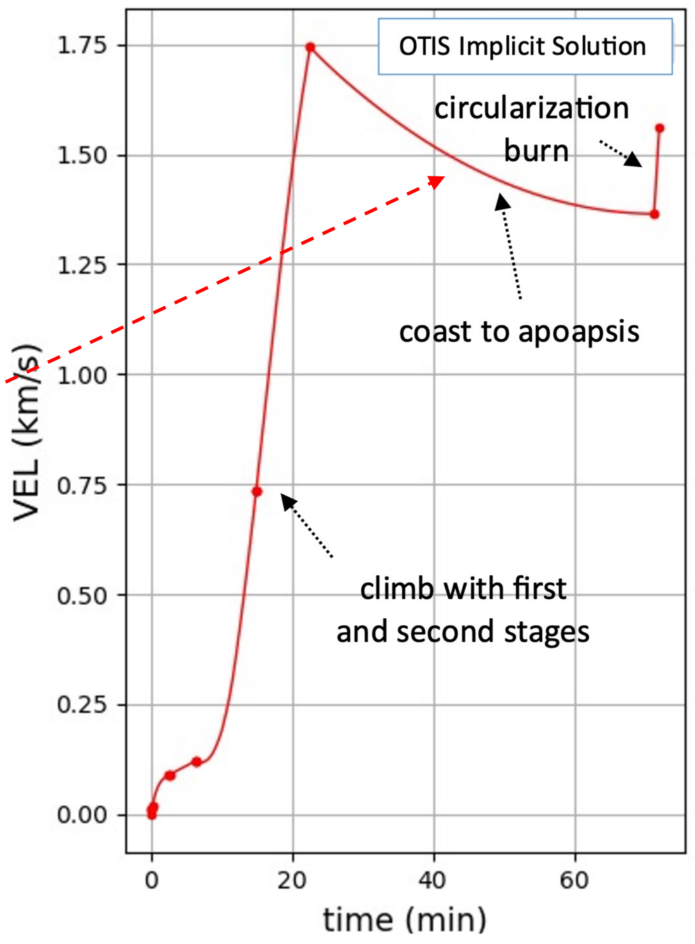

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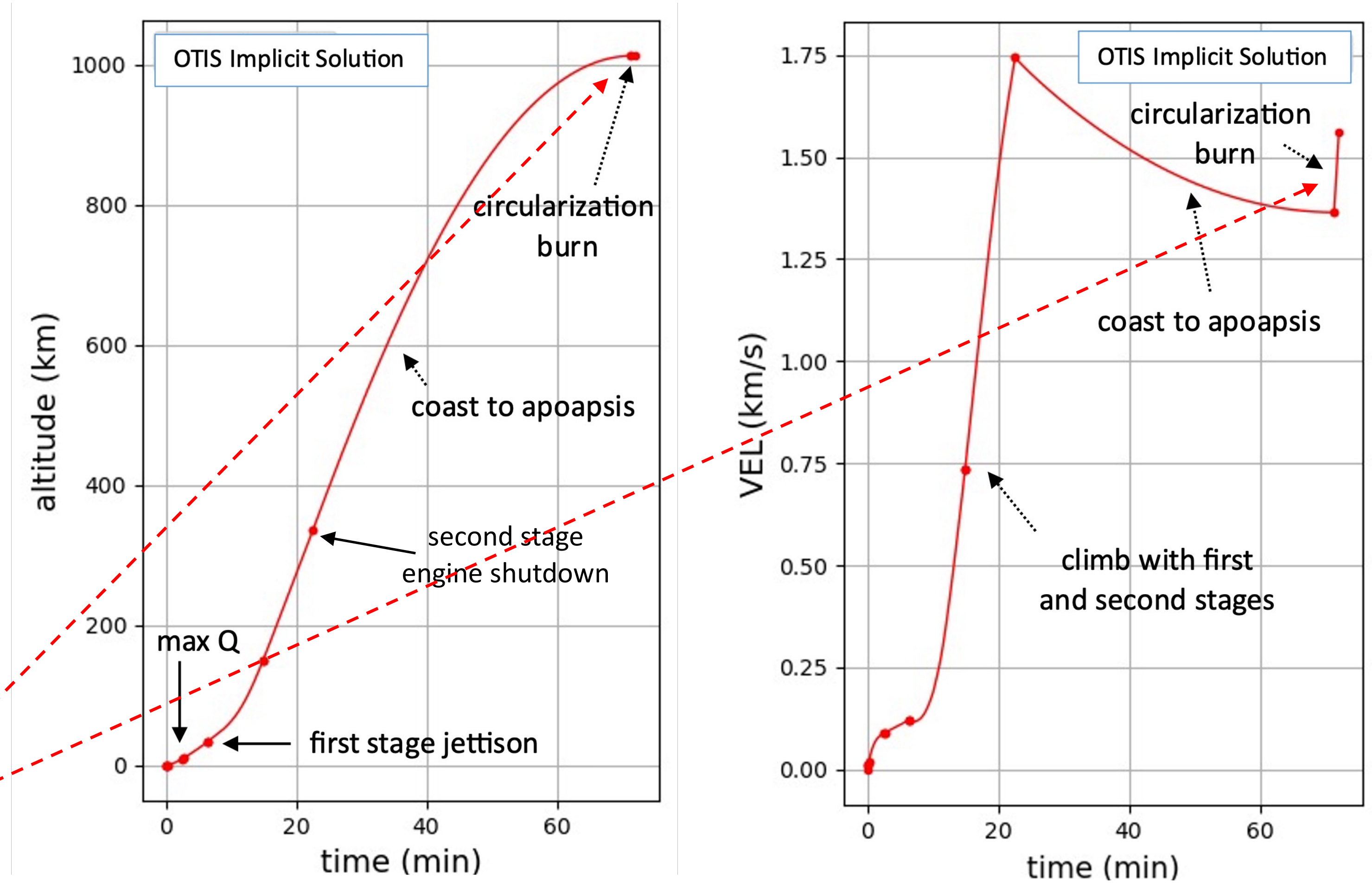

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