Lifting Entry and Atmospheric Flight (LEAF) Applications at Various Solar System Bodies

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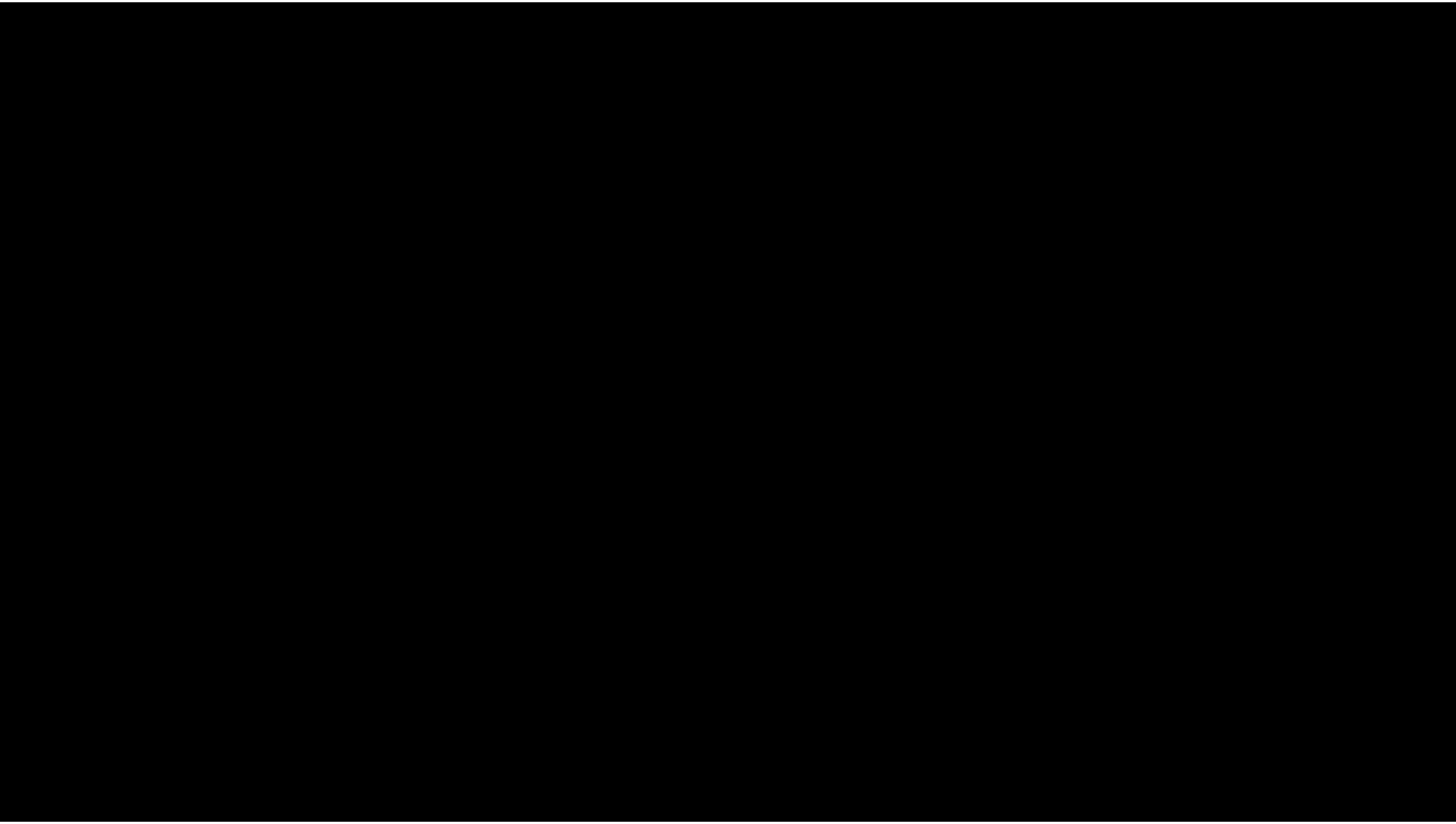
LEAF Video



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LEAF Is An Integrated Entry and Flight Vehicle for Extended Atmospheric Study

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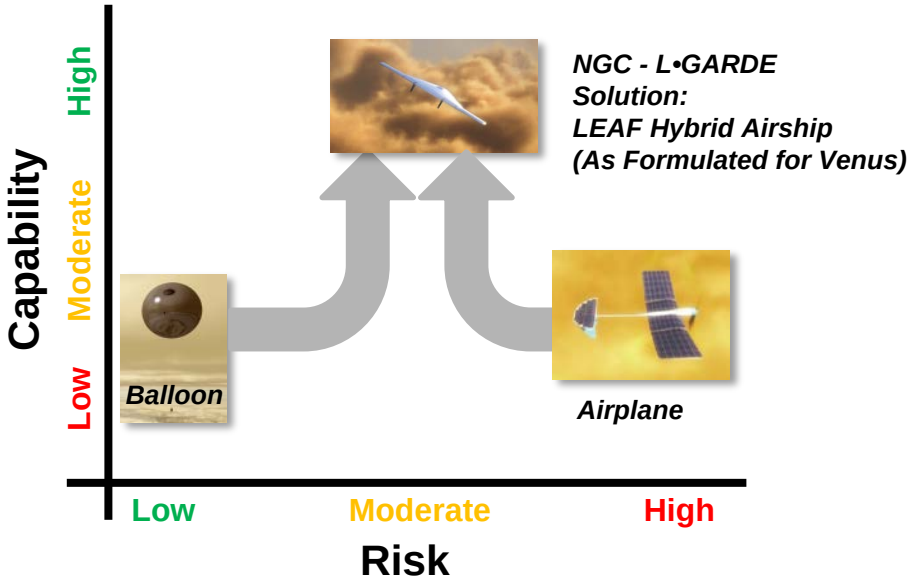
Lifting Entry Atmospheric Flight (LEAF) System



Venus Atmospheric Maneuverable Platform (VAMP)

LEAF Features and Capabilities

The first planetary exploration "Sky Rover"

- Lifetime of months to years for extended science ops
- 3D (latitude, longitude, altitude) directional control

Maximizes payload accommodation

- Benign entry eliminates large mass impact of aeroshell
- Enhanced payload mass and power capability compared to balloons and deployable aircraft
- Payload mass and power are flexible and tradable with vehicle altitude performance
- Some instruments can safely operate during benign entry phase

LEAF Risk Advantages

Safe mode / power failure / propulsion failure all produce passively floating state

- Sinks to altitude of 100% buoyancy (52 km on Venus)

Reduces number of mission critical events

- Deploys and checks out slowly while in orbit, prior to atmospheric entry
- Entry is slow and generates minimal loads
- Simple day/night concept of operation and power cycling

Terrestrial demos can retire most technology risks

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LEAF Targets and Missions

- The LEAF concept is applicable to any solar system body with an atmosphere
- This talk focuses on Venus, Titan, and Mars
  - Greatest amount of work to date has focused on Venus (VAMP)

Images credit: NASA

- Long duration flight at variable altitudes with revisit capability
- Atmospheric formation and evolution
- Characterization of atmospheric super-rotation and global circulation
- Determination of the temporal composition of “greenhouse” aerosols and gases

Greatest Focus Area: VAMP

- Long-lived flight at low altitudes with revisit capability
- High resolution surface imaging
- In-situ measurements of precipitation, fog, volcanism, etc
- Controlled, targeted delivery of boats/landers to surface

- Controlled, targeted delivery of cargo (e.g., rovers, landers, supplies, etc.) to surface
- Maneuverable glider

- High altitude atmospheric science
- Surface science and/or support
- ISS experiment return
- Astronaut emergency return
- Low-g life science experiment return

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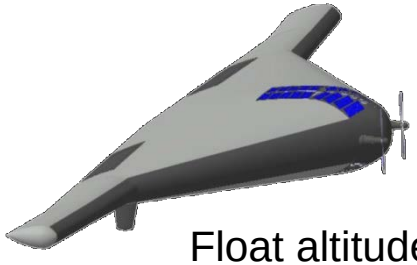
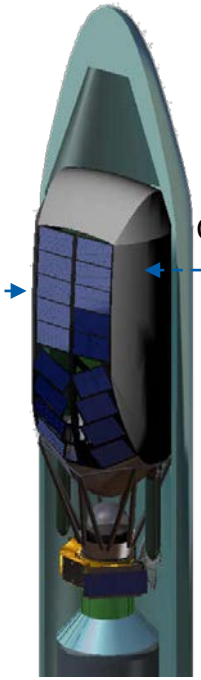
Venus Atmospheric Maneuverable Platform (VAMP) Vehicle Overview

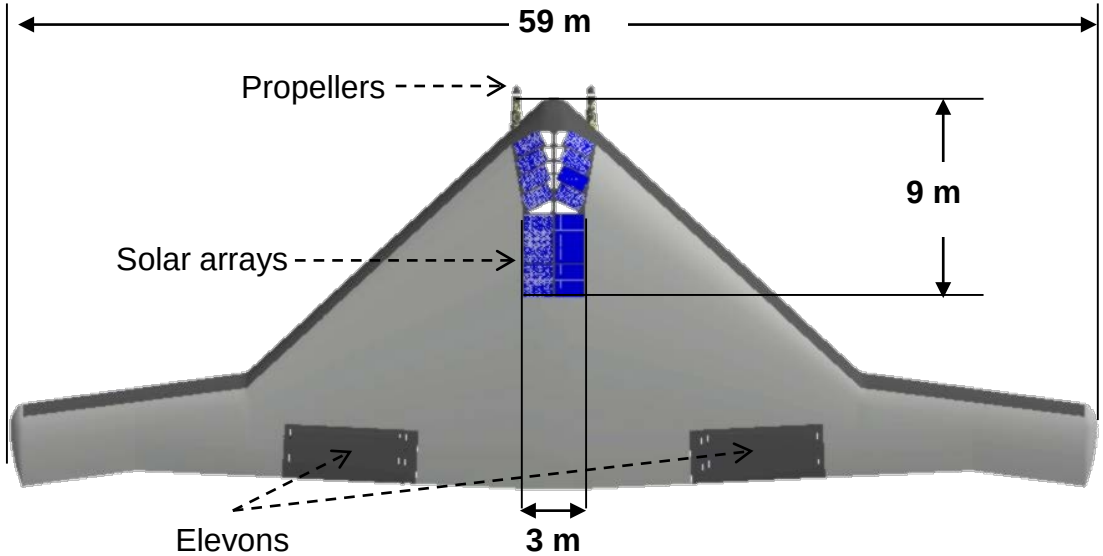
- Deployable Delta Planform
  - Stows in 5 m long fairing
  - Wingspan: 59 m
  - Volume: 752 m^3
  - Mass: 880 kg
  - Ballistic coefficient: < 10 kg/m^2

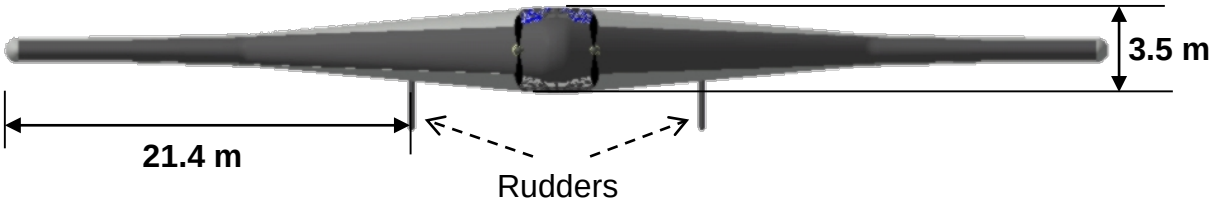


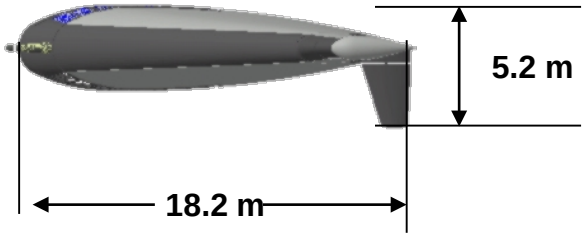
Float altitude: 52km

Stowed Configuration
Atlas V 5m Long Fairing









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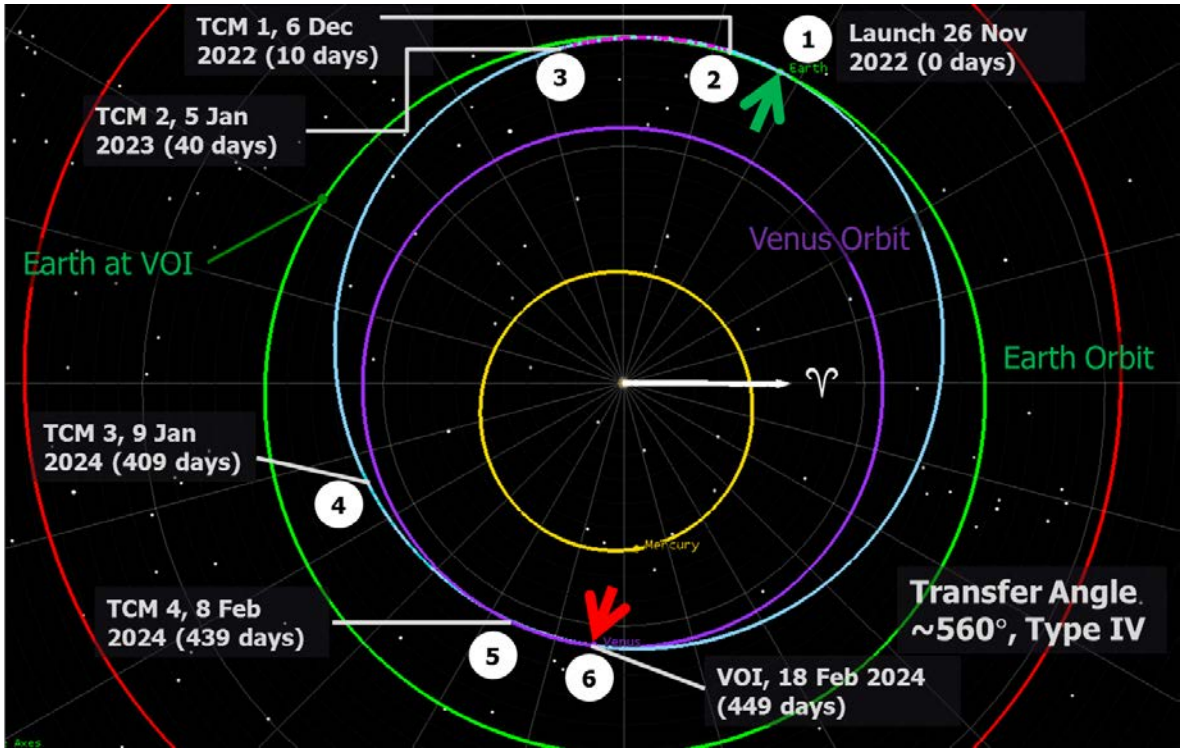
Venus Launch and Transit

- Type -III/-IV Trajectory
  - 449 days transit time
  - Longer than a Type I or II but allows 33% more post-VOI mass
  - C3 = 9.45 km^2/sec^2
  - $V_{arrival}$ = 10.6 km/sec
  - Recurs every 19 months (Nov 26, 2022 shown)
- Venus Orbit Insertion (VOI)
  - ΔV = 780 m/s
- Orbit Lowering
  - ΔV = 142 m/s
  - Final deployment orbit = 135 x 670 km
  - Final orbital speed = 7.4 km/sec at pericytherion
- Launch Vehicle = Atlas V 551
  - Lift capability to a C3 of 9.45 km^2/sec^2 = 5,046 kg
  - Fuel fraction to perform ΔVs = 28%
  - Total mass delivered to deployment orbit = 3,550 kg
  - VAMP = 880 kg, leaving 2,470 kg of mass for orbiter, orbiter fuel, and margin



(#) Numbers indicate events

TCM = Trajectory Correction Maneuver

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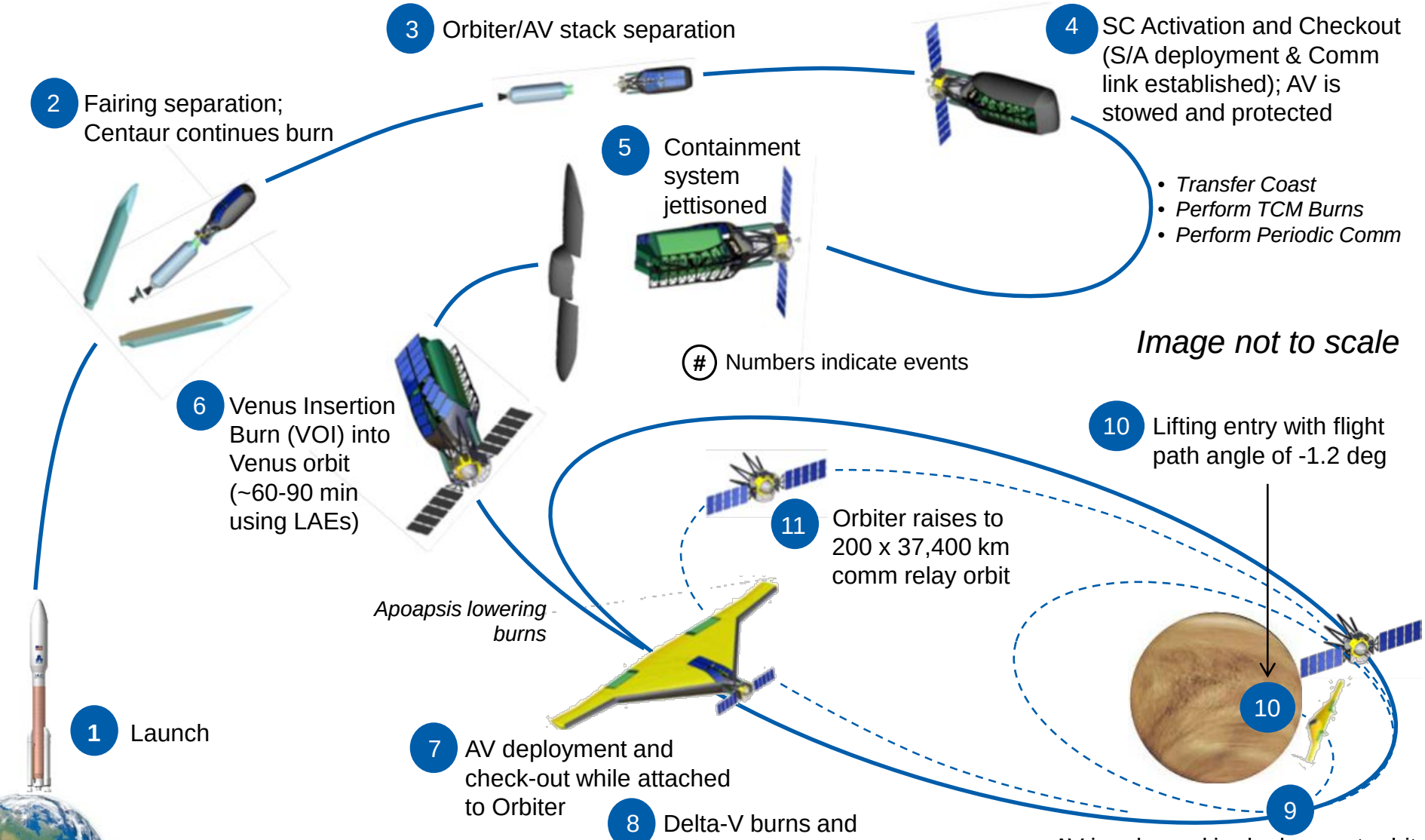
Notional VAMP Mission Sequence



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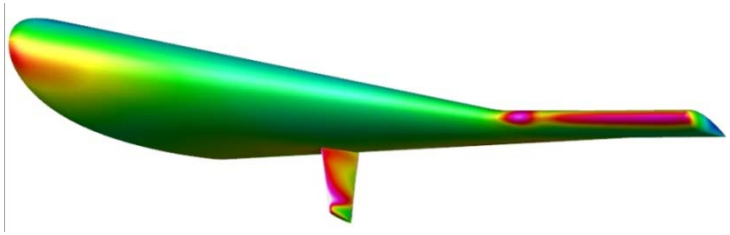
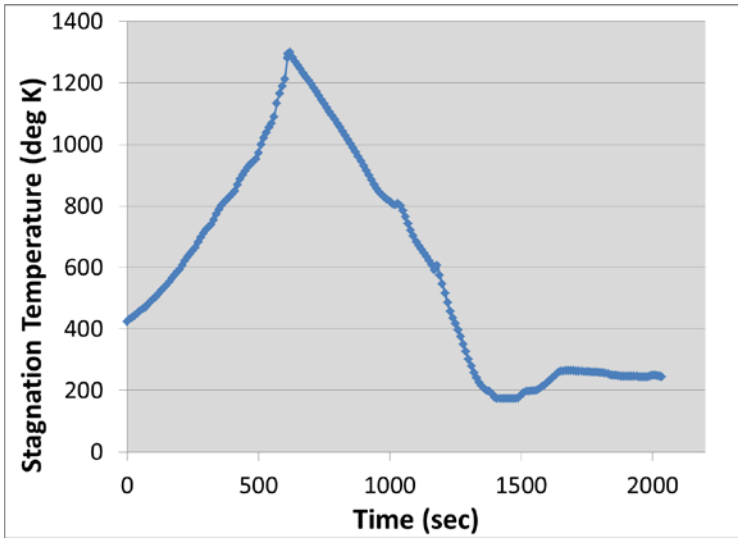
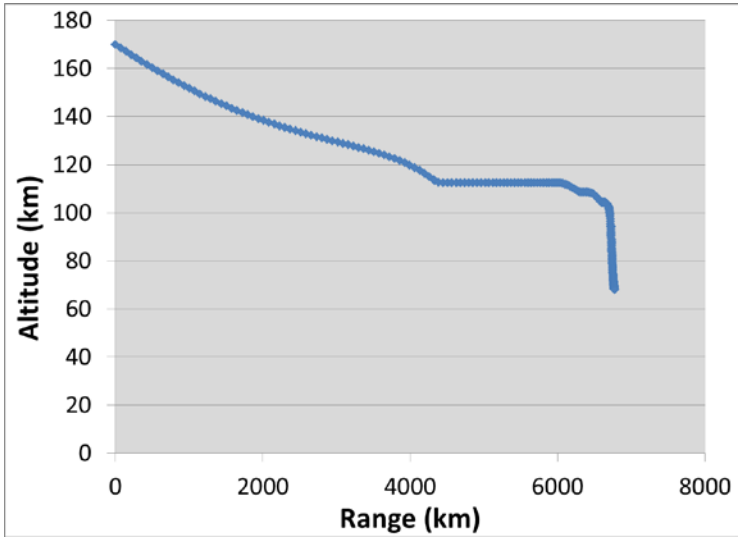
Venus Lifting Entry

- Modeling Assumptions
  - Venus atmosphere used for aerodynamic coefficients
  - Angle of attack = 20 to 30 degrees
  - Free molecular flow for Knudsen number (Kn) > 10
  - Full Navier-Stokes based aerodynamics for Kn < .001
  - Bridging equations for .001 < Kn < 10
- Lifting Entry Modeling Results
  - Max stagnation temperature = 1300 K
  - Integrated head load = 4400 J/cm^2
  - Max heat rate = 12.1 W/cm^2
  - Max deceleration = 2.5 g
  - Entry/descent time = 34 min
  - Entry path range = 7000 km







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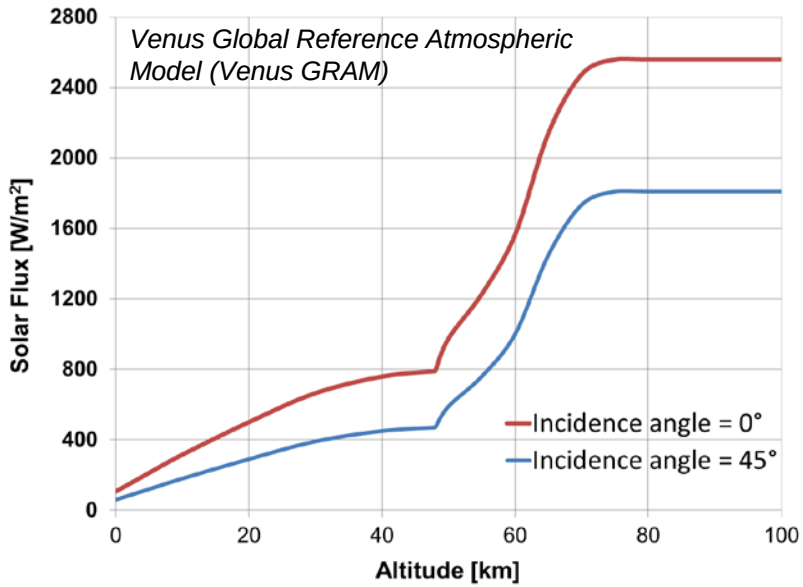
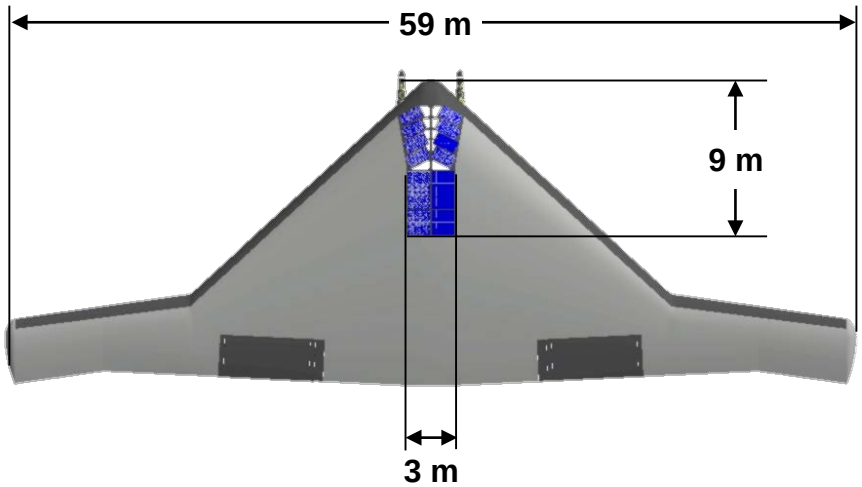
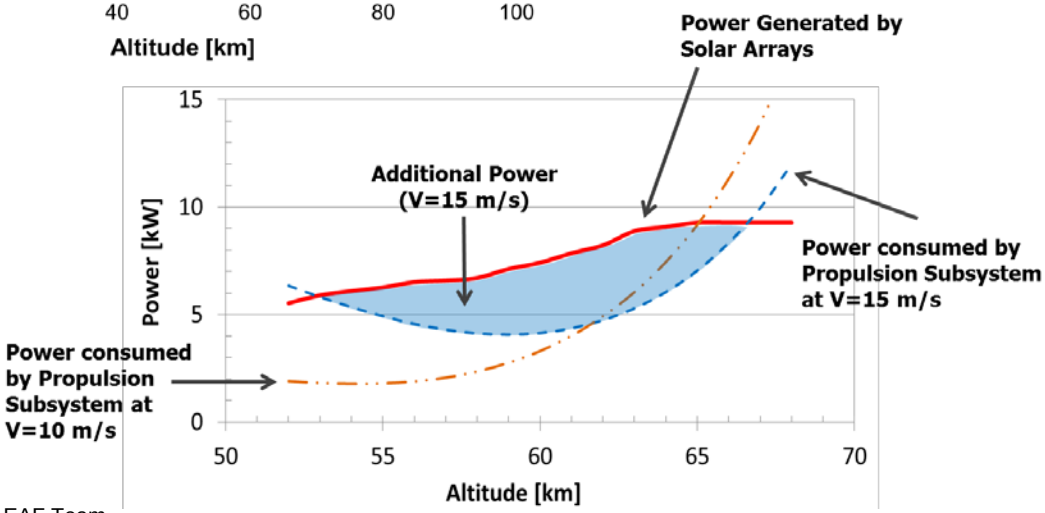
Power Availability

- Plenty of sunlight at Venus
  - 15 square meters of solar panels generates 8+ kW of power







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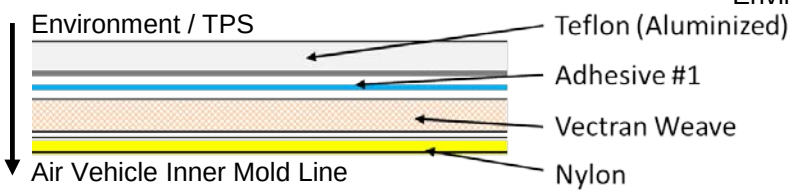
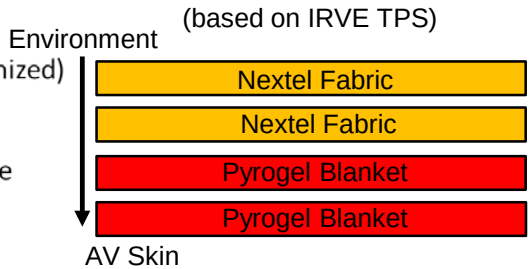
Skin Material & Thermal Protection System

- Skin Material Layup
  - Laminate based on NASA Venus balloon work
  - Leak rate ~.001 $m^3/m^2/day$
- Flexible Thermal Protection System (f-TPS) Layup
  - Fabric based on NASA Hypersonic Inflatable Aerodynamic Decelerator (HIAD), recently demonstrated by the Inflatable Reentry Vehicle Experiment (IRVE-3) flight
  - Only required along leading edges and stagnation points

Current Air Vehicle Skin Laminate
(based on JPL Venus Balloon work)



Current TPS
(based on IRVE TPS)



Possible Alternative TPS
(based on NASA GEN 2 HIAD TPS)
SiC fabric
Carbon felt
Kapton/Zylon laminate

Material Layup

	Location	Material	Purpose	Tmax (K)
Thermal Protection System (TPS)	Outer most	3M Nextel 312, AF-10	High temperature insulator	1,478
		Pyrogel XT-E	Moderate temperature insulator	923
Air Vehicle Skin		Teflon (metalized with Aluminum)	Chemical protection	533
		Aluminum (metalized Teflon inner surface)	Reflectant	933
		Vectran	Structural reinforcement	493
	Inner most	Nylon	Gas barrier	463

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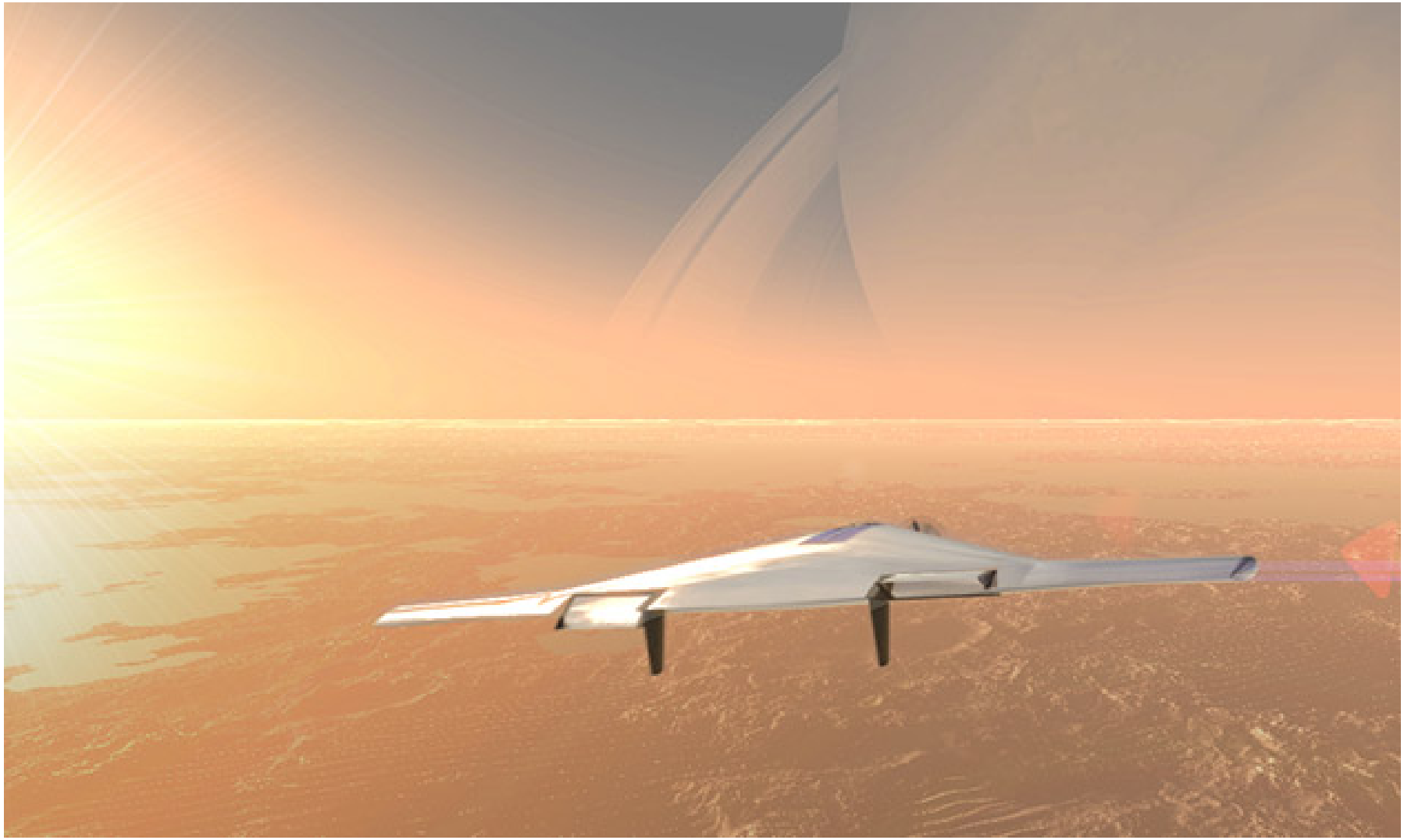
T-LEAF: Titan - Lifting Entry & Atmospheric Flight



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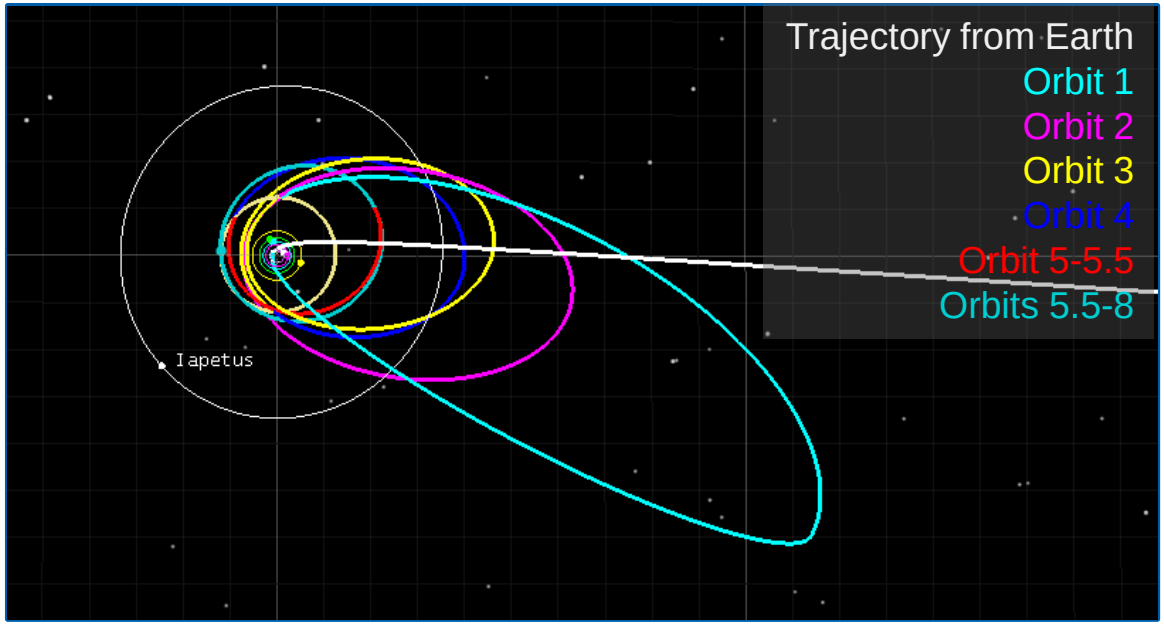
Titan Transit Trajectory

- Earth-Saturn Trajectory
  - "Cassini-like"
  - C3 = 16.5 km^2/sec^2
  - Transit time = 7 yrs
  - Deep space maneuvers ΔV = 750 m/s
  - $V_{arrival}$ = 28.4 km/sec
- Saturn Orbit Insertion (SOI)
  - ΔV = 657 m/s
- Titan Transfer Preparation
  - ΔV = 1052 m/s
  - V_{final} = 2.4 km/sec
- Titan Orbit Insertion (TOI)
  - ΔV = 575 m/s
  - Final deployment orbit = 780 x 5000 km
  - Final orbital speed = 1.8 km/sec at periapsis
- Launch Vehicle = Atlas V 551
  - Lift capability to a C3 of 16.5 km^2/sec^2 = 4,447 kg
  - Fuel fraction to perform ΔVs = 66%
  - Total mass delivered to deployment orbit = 1,662 kg
  - T-LEAF = 400 kg, leaving 1,262 kg of mass for orbiter, orbiter fuel, and margin



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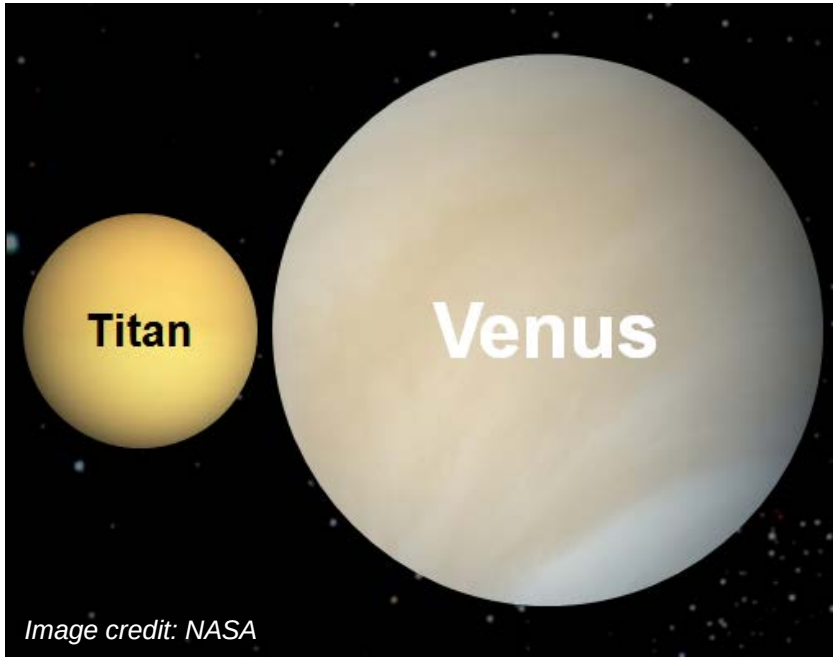
Titan Atmospheric Entry

- Titan Entry Conditions Compared to Venus
  - Entry velocity: 1.8 km/sec vs. 7.4 km/sec
  - Gravity at 200 km: 1.2 m/sec^2 vs. 8.3 m/sec^2
  - More diffuse, extended atmosphere
- Implications for Lifting Entry
  - Entry heating is 90% less than Venus
  - Allows higher ballistic coefficient, i.e. more mass per area



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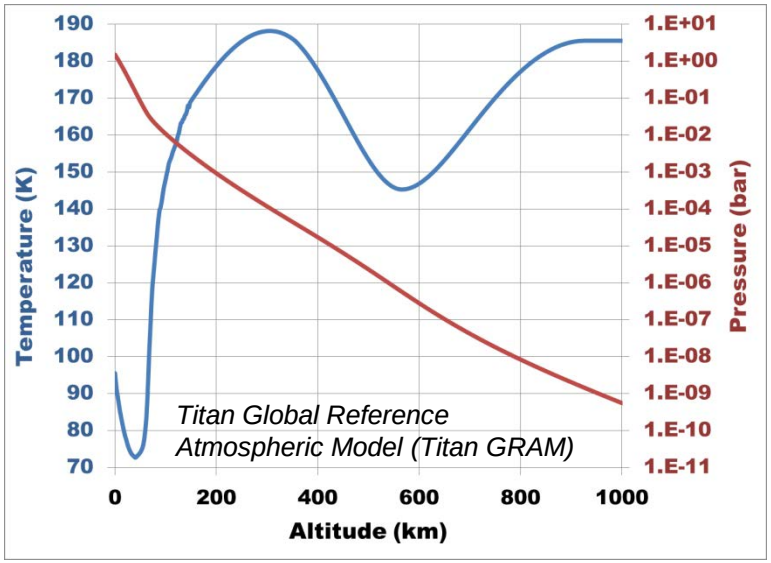
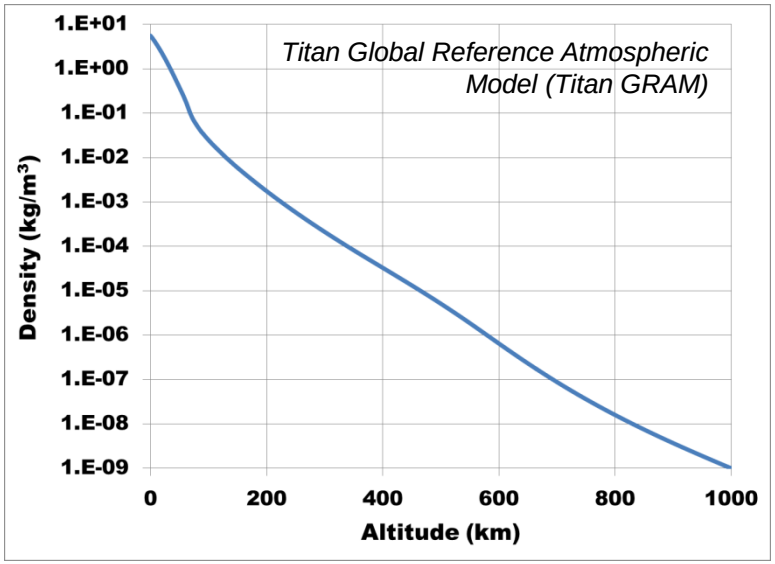
Titan Temperature, Pressure, Density, and Solar Flux

- Temperature, Pressure and Density: Titan vs. Venus
  - Highest operational temperature: 90K at 3 km altitude vs. 350K at 50 km altitude
  - Highest operational pressure: 1.3 bar at 3 km altitude vs. 1.1 bar at 50 km altitude
  - Highest operational density: 4.9 kg/m^3 at 3 km altitude vs. 1.6 kg/m^3 at 50 km altitude
- Solar Flux
  - Titan receives only 0.5% of the solar flux at Venus – Bring your own power!





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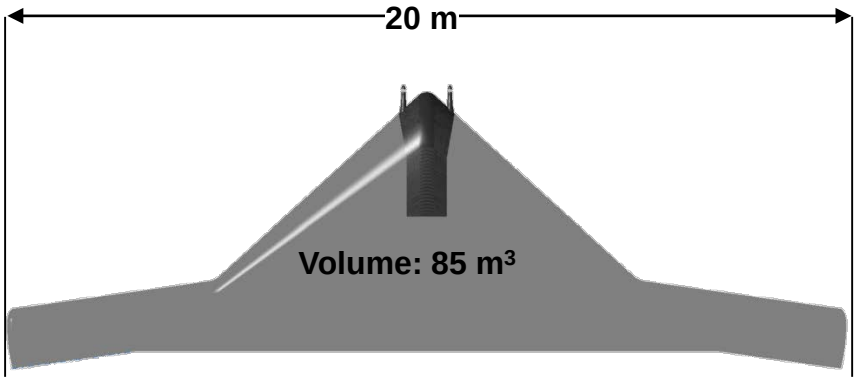
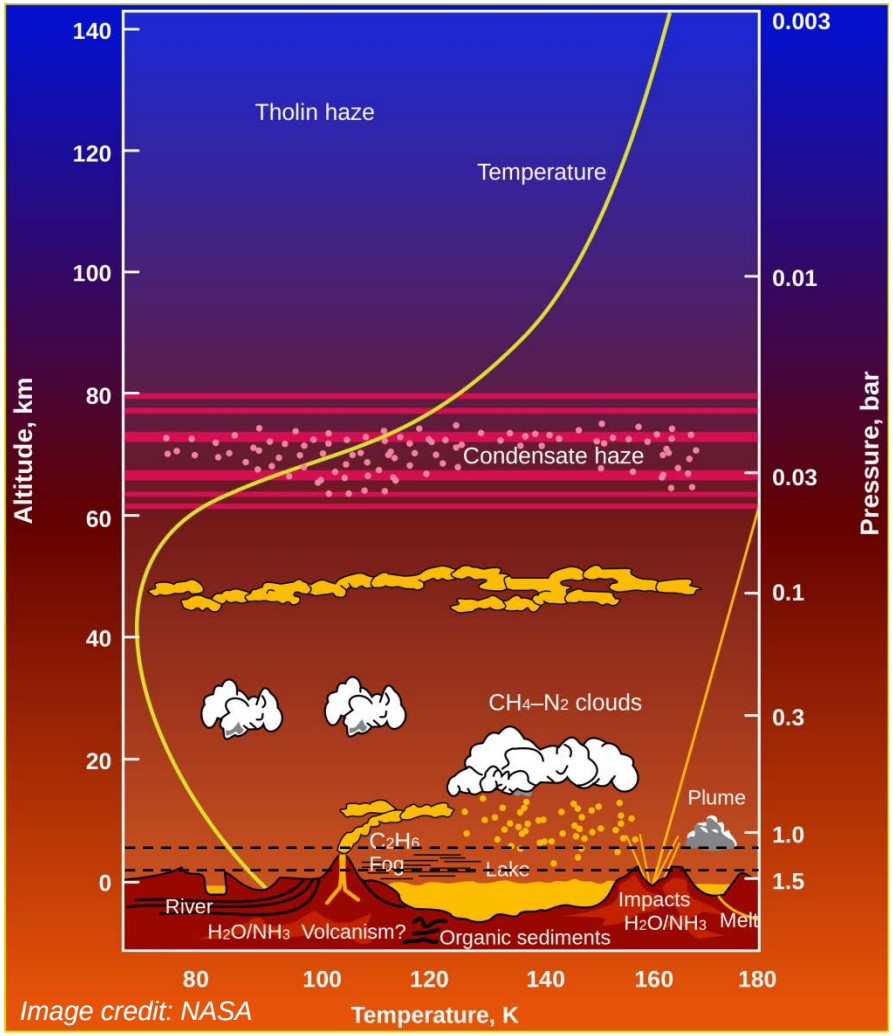
Low Altitude T-LEAF

- Air Vehicle Specifications
  - Mass: 400 kg
  - Wingspan: 20 m
  - Volume: 85 m^3
  - Power: 250 W
    - Based on two MMRTGs
  - Full buoyancy altitude: 3 km
    - T = 90K, P = 1.3 bar, ρ = 4.9 kg/m^3
  - Max flight altitude: 5 km





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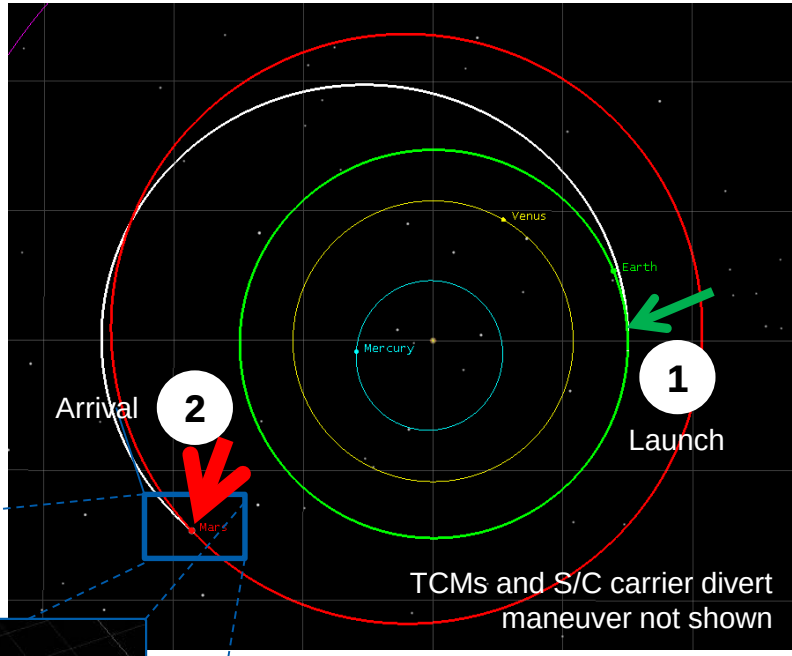
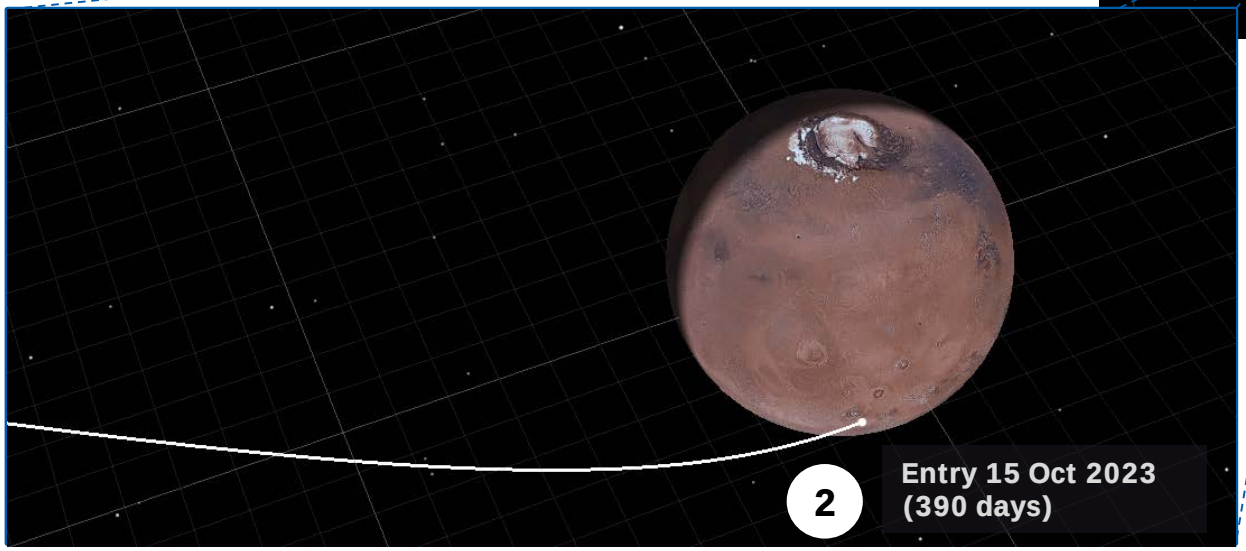
Mars Transit Trajectory

- Type-II Trajectory
  - 13-month transit time
  - C3 = 14 km^2/sec^2
  - $V_{arrival}$ = 5.7 km/sec
  - Recurs every 26 months (Sep 2022 launch shown)
  - Direct Entry (no orbit insertion required)
- Launch Vehicle = Atlas V 401
  - Lift capability to a C3 of 14 km^2/sec^2 = 2,200 kg
  - Fuel fraction required for trajectory correction and divert maneuvers = 7%
  - Total dry mass delivered to direct entry = 2050 kg
  - M-LEAF = 1200 kg, leaving 850 kg of mass for the carrier spacecraft





- M-LEAF Vehicle
  - Wingspan: 92 m
  - Volume: 8200 m^3
  - Mass: 1200 kg
  - Max path range: 10,000 km
  - Full buoyancy not possible
  - Targeted delivery of payloads to surface

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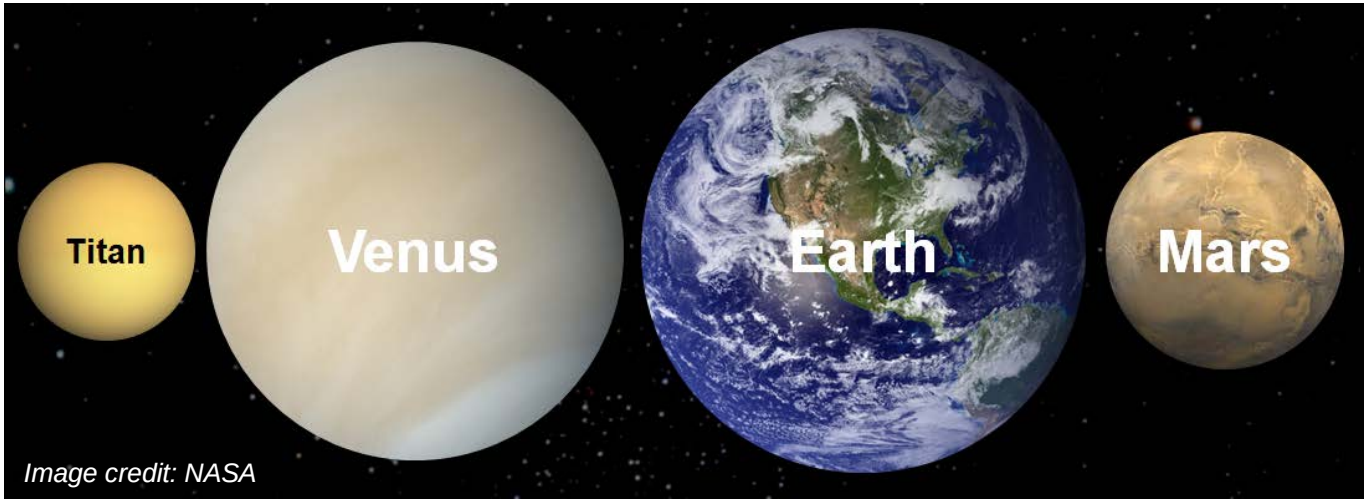
Conclusion

- Venus
  - Extensive analysis of VAMP
  - Advantages: Plenty of sunlight, ease of access (Atlas V, 1.5 year transit)
  - Disadvantages: Inhospitable temperature and pressure below 50 km altitude
- Titan
  - Less extensive but promising analysis of T-LEAF
  - Advantages: Hospitable temperature and pressure at all altitudes, dense atmosphere, lower gravity, gentle entry conditions
  - Disadvantages: Solar power generation not feasible, longer transit time
- Mars
  - Limited analysis of M-LEAF
  - Advantages: Direct entry, ease of access (Atlas V, 1 year transit), surface payload delivery
  - Disadvantages: Atmosphere too thin for full buoyancy



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