Fixed and Rotary Wing Flight of Small Air Vehicles on Mars, Venus, and Titan

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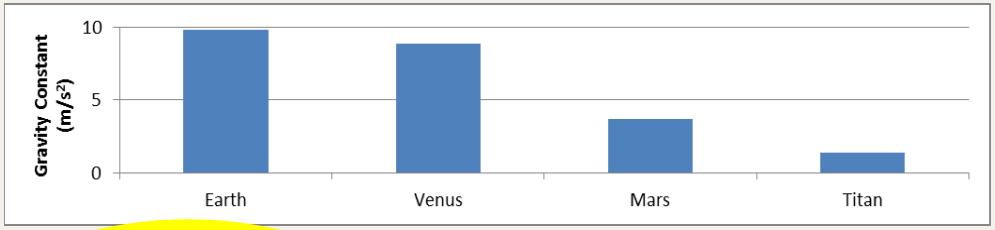
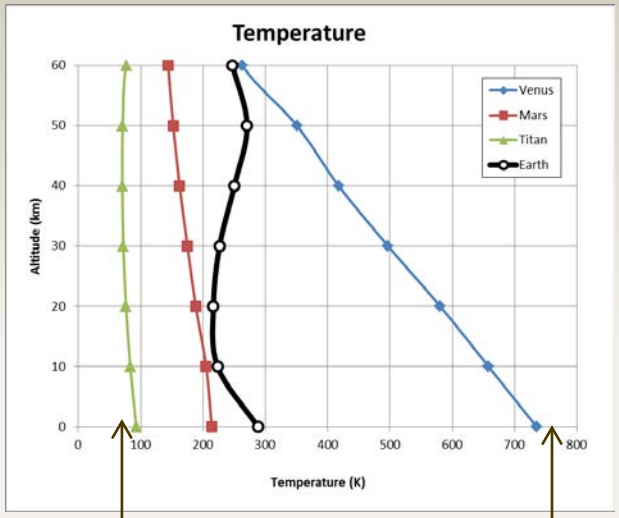
[#8081]

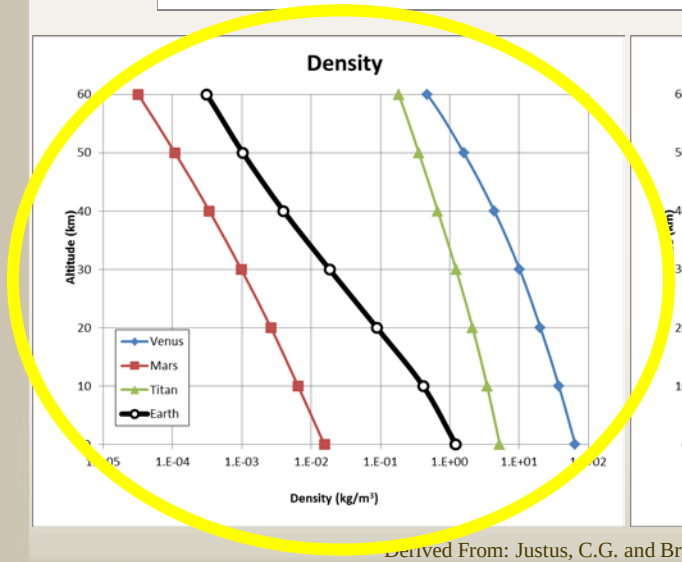
Earth, Venus, Mars, and Titan Parameters

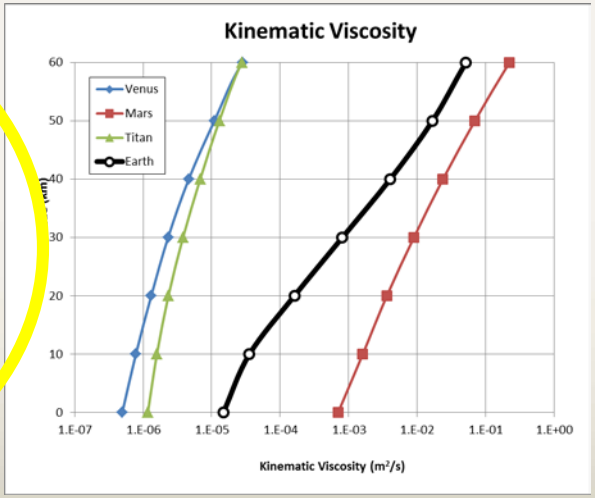


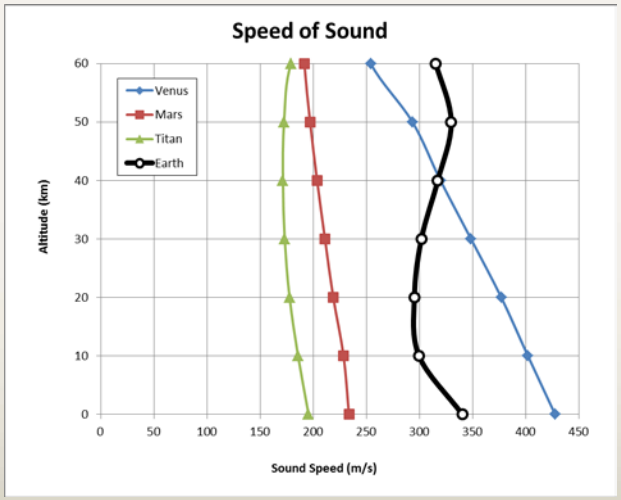


"LN2 on Earth"

"Kitchen Oven Clean Cycle"







Derived From: Justus, C.G. and Braun, R.D. (2007). Atmospheric Environments for Entry, Descent and Landing (EDL). MSFC-198.

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Dynamic Pressure, Lift and Drag

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Dynamic pressure is a measure of how much force per unit area you get when moving through a fluid.

$$q = \frac{1}{2}\rho U^2$$

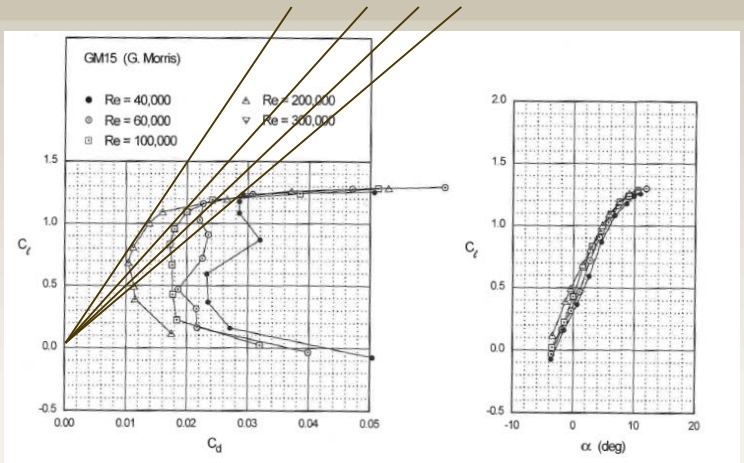
Lift Force $\quad L = (\frac{1}{2}\rho U^2)C_L A, \;\; C_L \sim O(1)$

Drag Force $\quad D = (\frac{1}{2}\rho U^2)C_D A$

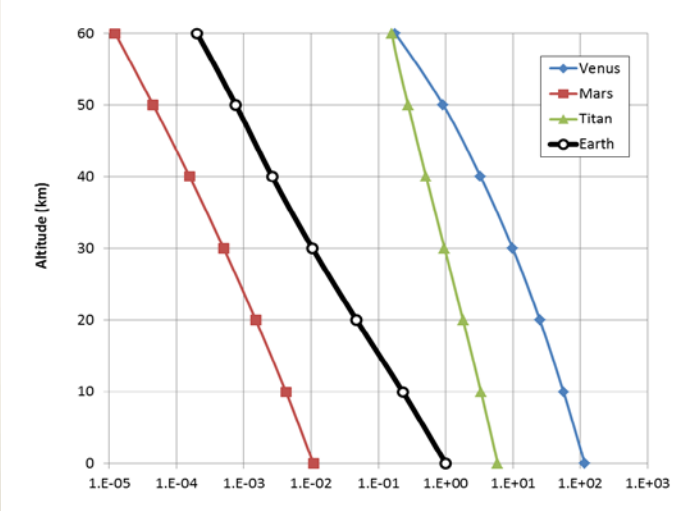
Weight $\quad W = mg$

Gliding flight $\quad L = W$

- Low density means you need to go **fast** or have a **large** lifting surface to get useful lift forces.
- High density means you go **slow** because otherwise you have to overcome large drag forces.



Selig, M.S., Guglielmo, J.J., Broeren, A.P., and Giguère, P., (1995) *Summary of Low-Speed Airfoil Data*, Vol. 1, SoarTech Publications.



$$\frac{\frac{1}{2}\rho\, a^2/g}{\left[\frac{1}{2}\rho\, a^2/g\right]_{e,0}}$$

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Reynolds and Mach Numbers (Subsonic)

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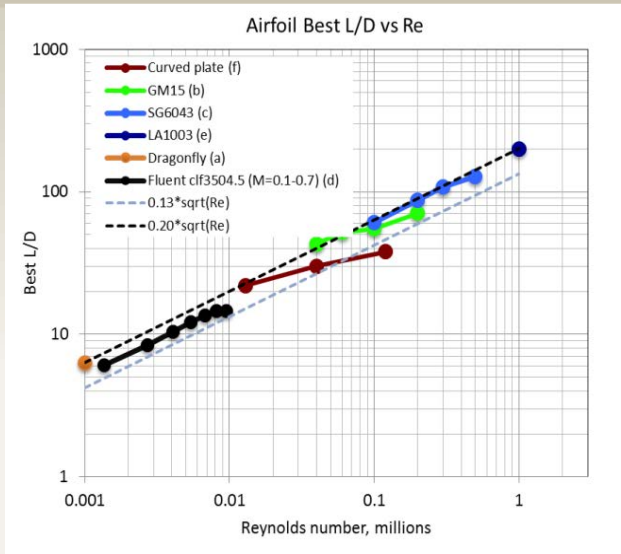
Reynolds Number

- 'The relative influence of inertial and viscous forces' $Re = \frac{\rho U L}{\mu} = \frac{UL}{v}$
- Useful to talk about the character of a flow, i.e., Flow Separation, Turbulence, Skin Friction, Lift and Drag
- Prediction of best airfoil performance.



(a) Wakeling, J.M., and Ellington, C.P. (1997) "Dragonfly Flight I. Gliding Flight and Steady-state Aerodynamic Forces," The Journal of Experimental Biology 200, 543-556.
(b) Selig, M.S., Guglielmo, J.J., Broeren, A.P., and Giguère, P., (1995) *Summary of Low-Speed Airfoil Data*, Vol. 1, SoarTech Publications.
(c) Lyon, C.A., Broeren, A.P., Giguère, P., Gopalarathnam, A., and Selig, M.S. (1998) *Summary of Low-Speed Airfoil Data*, Vol. 3, SoarTech Publications.

Mach Number

- Ratio of flow speed to speed of sound, M = U/a
- $\frac{C_{P,M}}{C_{P,i}} = \frac{1}{\sqrt{1-M^2}}$ (Glauert-Prandtl rule)
- Less Lift and significantly more drag above M~0.6
- Just stay below M=0.6-0.7

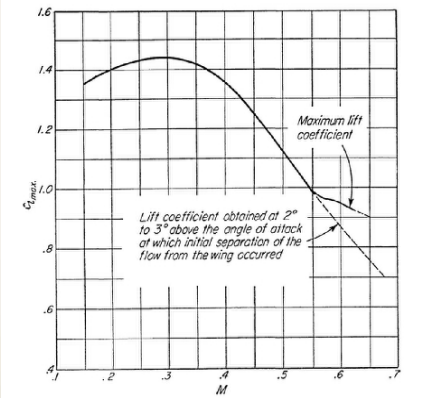


FIG. 171. Variation of wing maximum lift coefficient with Mach number.

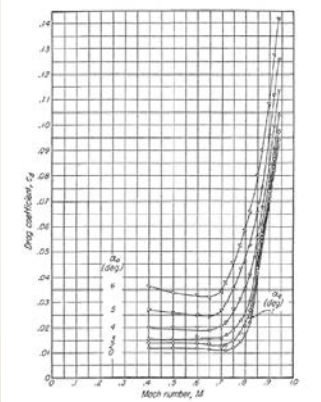


FIG. 170. Effect of compressibility on the drag of the NACA 0012-34 airfoil.

Abbott, Ira H.; Doenhoff, A. E. von (2012). Theory of Wing Sections: Including a Summary of Airfoil. Dover Publications. Kindle Edition.

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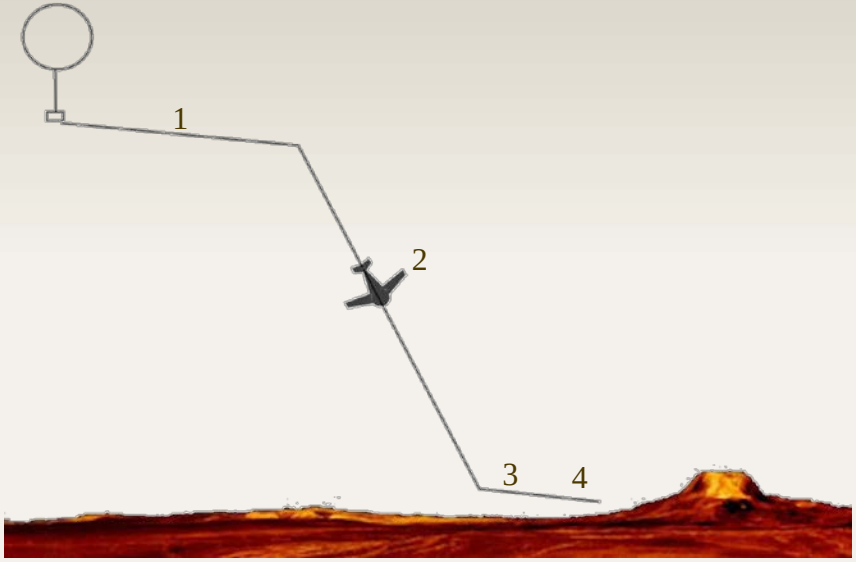
Venus

[#8081]

Mission: Near Surface Area Photography, Single Use Glider Sonde



- Release from 60 km altitude
- ~1 hours total flight duration
- 10km of linear coverage at 1-2km altitude
- 20kg total vehicle mass
- Spherical Pressure Shell 0.38m diameter.

- *High Temperatures → short flight*
- *High density → slow flight*
- *High Re → reasonable L/D*
- *Speed of sound not a driving factor*
- *Use a simple drag build for the glider*
- *FYI: mgh = 10MJ*

Phase	Altitude (km)	Description	Comments	Re/1e6	Mach	Speed (m/s)	Wind (m/s)	Time (min)	Cum Time (min)
1	50-60	Traverse	• Glide slope is 'best effort' ~ 9:1 relative to the wind. • Use simple drag build to determine glide slope.	0.7	0.3	80	75-50	20	20
2	2 to 50	Rapid Descent	• Vertical speed is limited by vehicle drag and speed of sound • Spoilers or Crow flaps are needed between 50 and 60km	1-3	0.6-0.1	190-50	75-0	10	30
3	1 to 2	Gather Data (Threshold)	• Glide with a > 10:1 glide ratio for 10km, take pictures • This phase sets the air vehicle glide performance requirement • Use simple drag build to determine glide slope	3.5	0.02	9	~0	20	50
4	0 to 1	Gather Data (Bonus)	• Continue gliding until impact with ground.	3.5	0.02	9	~0	20	70

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Approach

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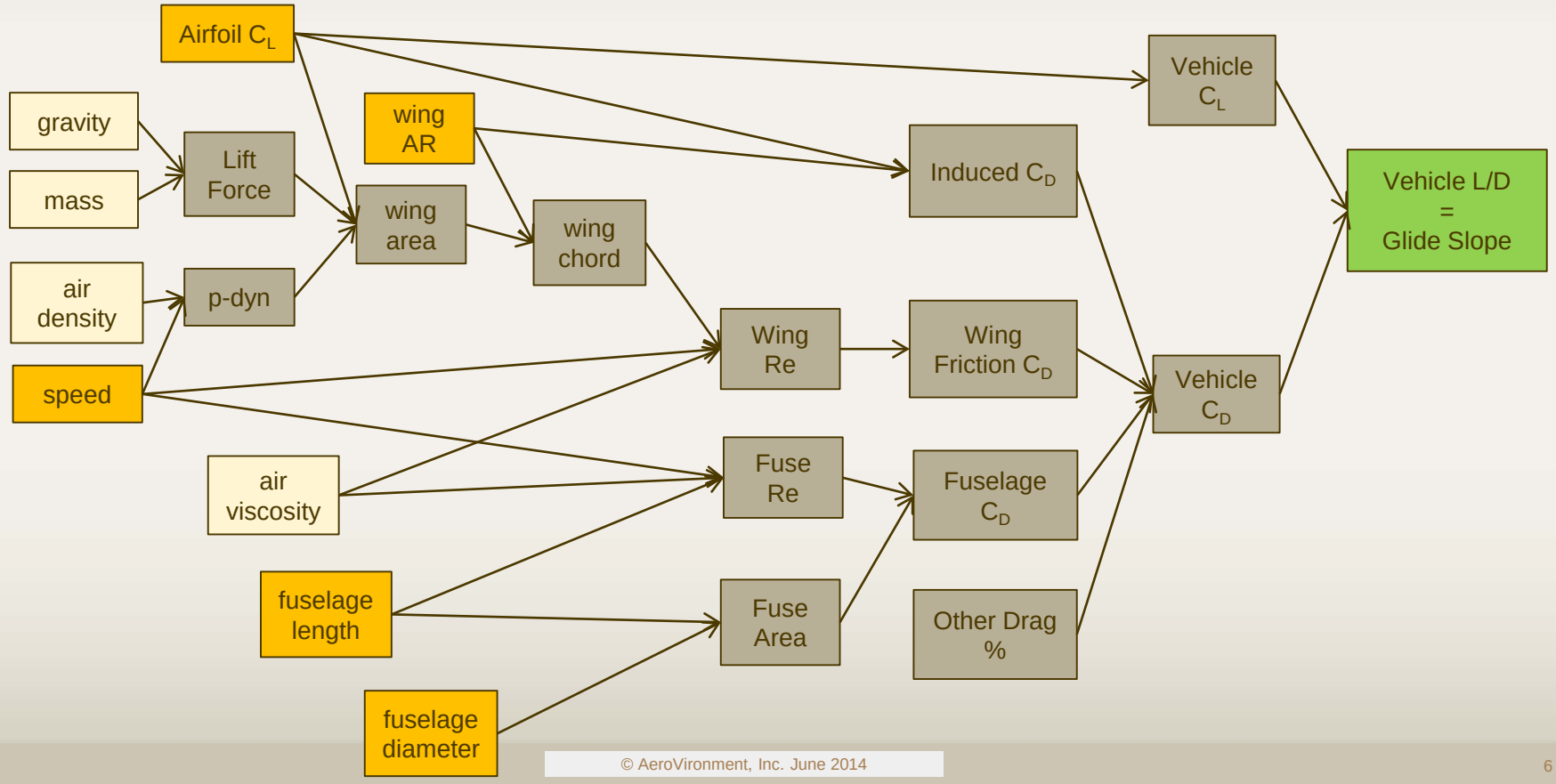
- Parameterize Air Vehicle
- Solve for fastest speed that will yield an L/D of 10:1 (to minimize flight time)
- Solve for terminal speed and time to descend to altitude.
  - Add drag brakes as needed to prevent exceeding M=0.6
- Solve for L/D at release altitude and compute time to transit.



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Titan

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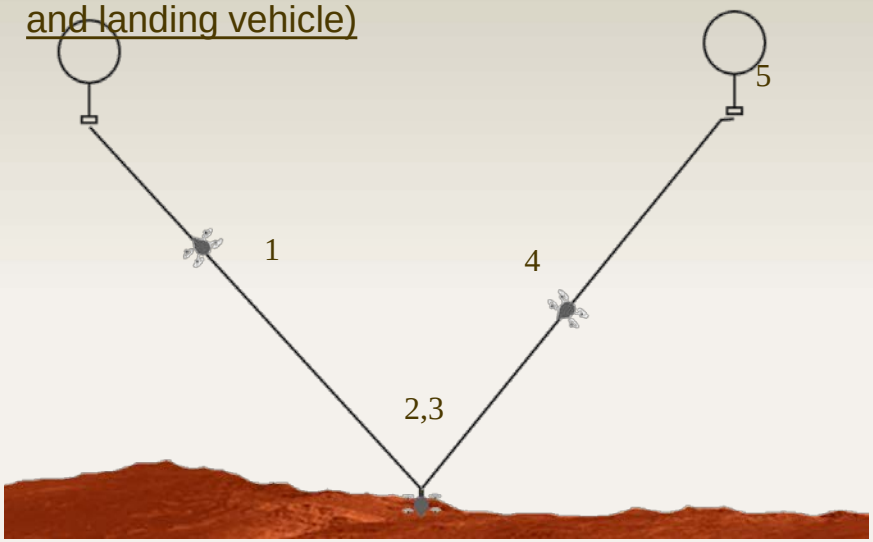
Mission: Sample and return (with vertical take off and landing vehicle)



- <10 kg total vehicle mass
- 10 km balloon altitude
- 2 m/s balloon speed
- 20W & 0.25kg for avionics & sensors

- *Multi-copter is a mechanically simple VTOL*
- *Low gravity → low penalty for climbing*
- *High density → low speeds, less mass in propulsion*
- *Low Temperatures → insulation, volume, and drag.*
- *Use momentum theory for VTOL performance*
- *Speed of sound not a factor*
- *Density ratio 1.5 from 0-10km → similar performance over alt.*
- *Low wind speeds → we can get back to our balloon.*

Phase	Altitude (km)	Description	Comments	Power (W)	Speed (m/s)	Wind (m/s)	Time (min)	Cum Time (min)	Cumulative Energy (Wh)
1	10-0	Descent	• Zero or negative (charging) propulsion power • Descent Rate can be controlled with rotors	20	11	2	15	15	5
2	0	Hover/Land	• Momentum Theory in Hover • rotor FOM = 75%, Disk loading = 100 Pa	100	0	0	5	20	13
3	0	Gather Data	• 5 minutes	20	0	0	5	25	15

4	0-10	Take off and climb	• Momentum Theory in Climb
			  • Rotor FOM = 75%, Same Rotor as above
			  • Constant Climb Rate
			• Add Fuselage Drag
				255	8	2	20	45	100

5	10	Hover and Mate with Balloon	• Momentum Theory in Hover • rotor FOM = 75%, Disk loading = 100 Pa	115	0	2	5	50	110

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Approach

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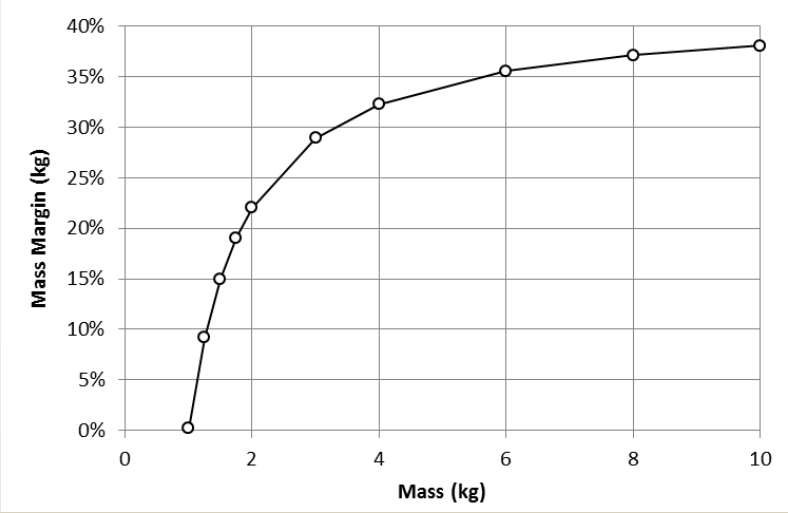
- Multi-copter configuration
- Momentum Theory for Hover and Climb
- We can design a rotor with a FOM = 0.75
- Disk loading (*T/A*) is 100 Pa
- Fuselage drag is like a sphere based on frontal area (used to estimate drag in climb)
- Airframe and propulsion is 50% of total vehicle mass.
- Fuselage density is around 300 kg/m^3
- JPL Avionics and Payload are 0.25kg and uses an average of 20W.
- No propulsion power is required for descent
- Motor efficiency is 85%, Controller is 95%.
- Compute Power consumption and battery mass using a specific energy of 100 Wh/kg

- Compute for a range of Vehicle gross masses - Remaining mass is margin

Momentum theory for rotors in hover and climb

Thrust	T
Density	ρ
Rotor Swept Area	A
Climb Rate	U
Figure of Merit	FOM
Induced Velocity	$u_h = \sqrt{T/(2\rho A)}$
Hover Power	$P_h = T\,u_h/FOM$
Climb Power	$P_c = \frac{T\left(\frac{1}{2}U+\sqrt{\left(\frac{1}{2}U\right)^2+u_h{}^2}\right)}{FOM}$



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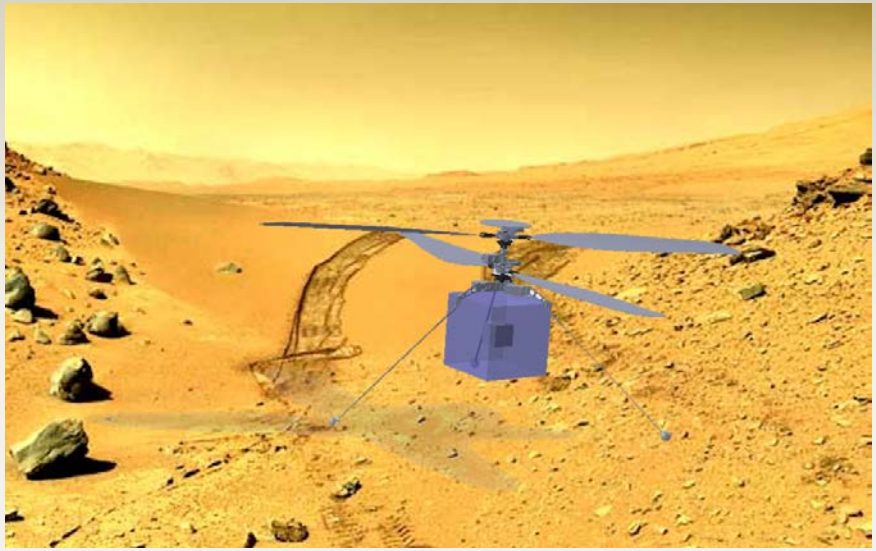
Mars

[#8081]

Mission: Demonstrate Aerial Rover-Like Capability



- Mars surface density and speed of sound
- Vehicle Mass = 1kg.
- Airframe and Propulsion < 500 grams
- Thrust > Weight

- *Low density → need high rotor speed*
- *Vehicle drag not significant in forward flight (or sitting on the ground)*
- *Rotorcraft allow high speed propeller, but can fly slow.*
- *Low speed of sound → limits rotor speed → large rotors → increase weight...*
- *Low Reynolds number → limits efficiency and flight time.*
- *HOGE requires the most power*

Mass	1 kg	Design Mass. 50% for avionics, sensor, batteries, 50% for airframe and propulsion.
Rotor Diameter	1.1m	Fits in box when folded
Nominal Rotor Hover Power	130W	Nominal over operating envelope
Rotor Peak Power Margin for Maneuvering	50%	Accounts for maneuvering acceleration and gust compensation
Design Density	0.012 – 0.015 kg/m^3	Variation to account for altitude, temperature, latitude, etc.

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Approach

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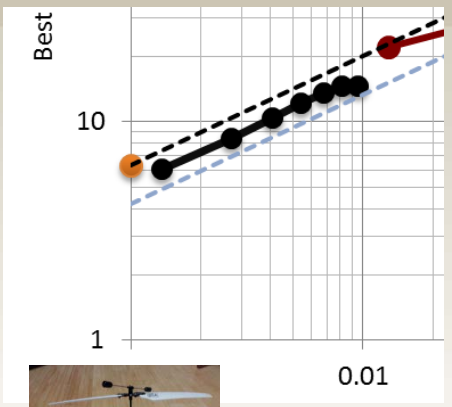
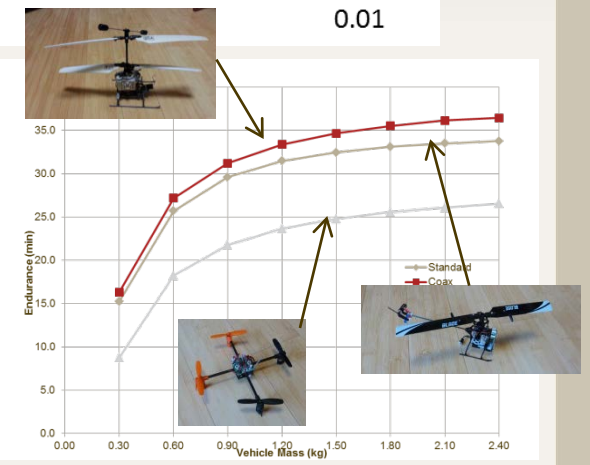
- Estimate Rotor Performance
  - Estimate airfoil performance at design conditions
  - Use propeller design & analysis code to estimate propeller performance and design blades for best efficiency, vary and constrain diameter, chord, tip speed

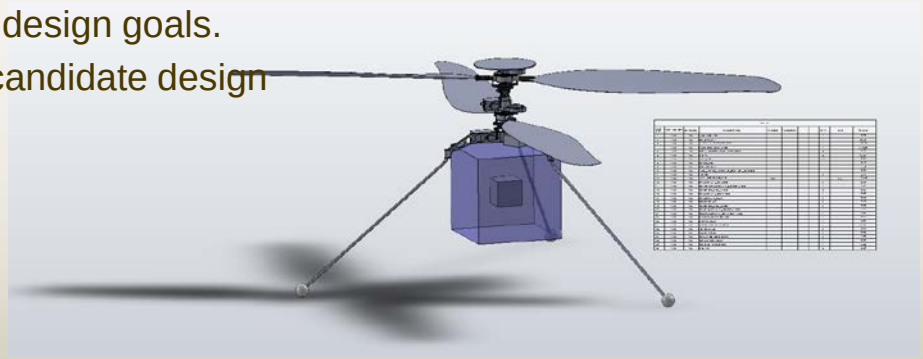
- Optimize Potential Configurations
  - Employ ‘rubber’ mass models for many parts.
  - Optimize parameters for maximum endurance; constrain tip speed, solidity, disk loading.

- Increase Fidelity of Estimates
  - Use CFD (Fluent) to test the performance of a candidate airfoil for low Re.
  - Test candidate airfoil on a rotor in mars-like atmosphere in JPL’s 10ft Vacuum Chamber – Performance was only 10% lower than expected from Fluent airfoil analysis and within design goals.
  - Develop preliminary Solid Model and BOM for candidate design
  - Evaluate masses against design goals

- Revisit Assumptions
- Test Optimized Rotor Design







End

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- There is lots of margin when considering an air vehicle on Venus and Titan. Non-aero factors will drive these designs.
- Mars does not have much margin. We will need to fight for every gram and every percent to ensure success.
- Questions?

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